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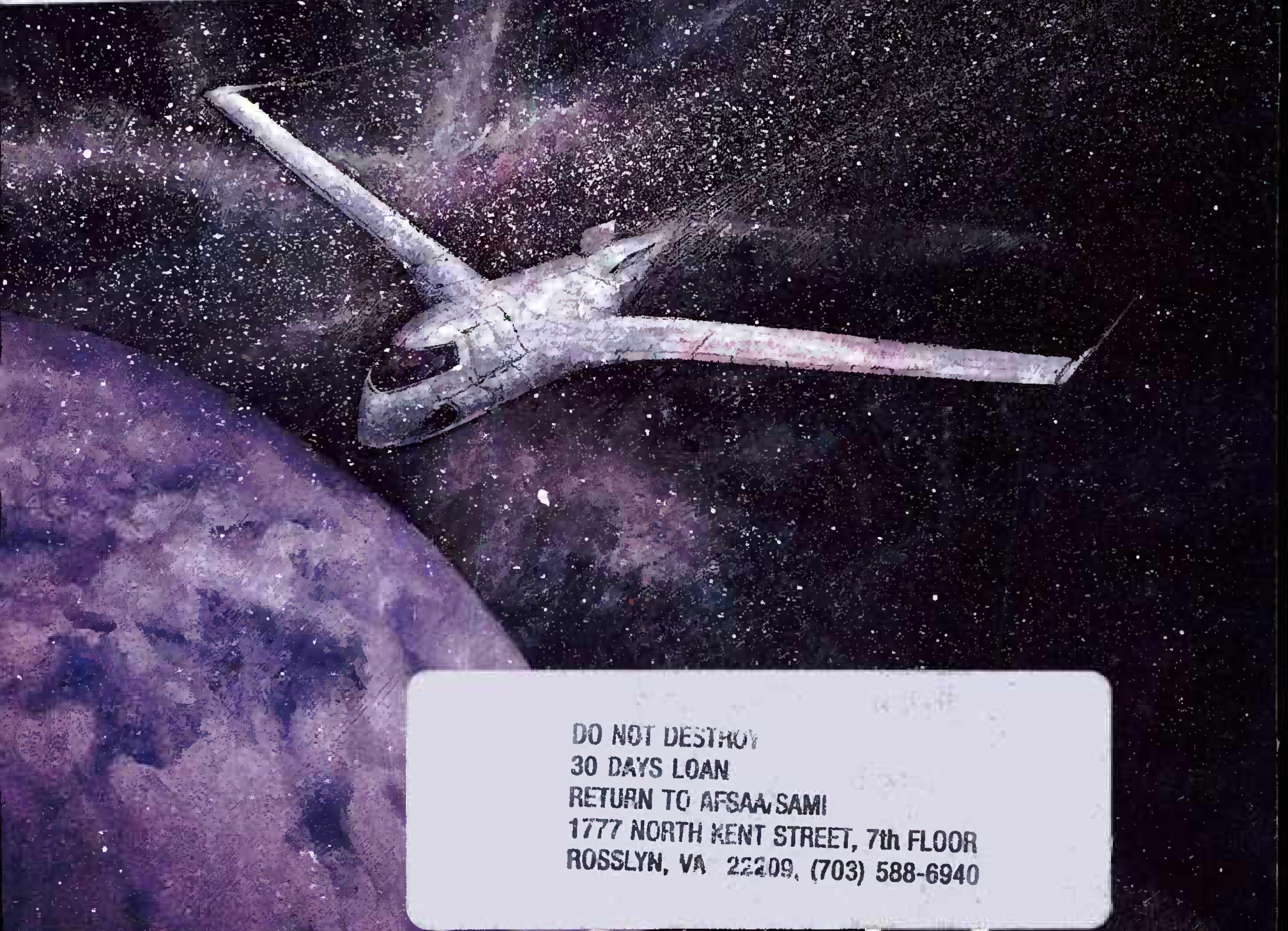

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AIR AND SPACE POWER FOR THE 21ST CENTURY

DIRECTED ENERGY VOLUME

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NEW WORLD VISTAS

AIR AND SPACE POWER FOR THE 21ST CENTURY

DIRECTED ENERGY VOLUME

This report is a forecast of a potential future for the Air Force. This forecast does not necessarily imply future officially sanctioned programs, planning or policy.

Abstract

Directed energy weapons, both lasers and microwaves, will have widespread application over the next few decades. A substantial technical data base now allows confident anticipation of weapon applications. Initial airborne weapons to provide boost-phase defense against ballistic missiles and defense of aircraft against missiles will lead the way to space-based, or space-relayed, weapons. Global presence with weapons capable of destroying or disabling anything that flies as well as most unarmored ground targets will drive a new warfare paradigm.

This volume discusses directed energy applications that are most probable as well as most important in three time periods: 10, 20, and 30 years. The technologies which should be supported to enable these applications are discussed leading to several conclusions and recommendations. Our intent is that these recommendations are sufficiently detailed to provide rapid definition of technology thrusts in laboratory programs. Reference is also made to a number of classified annexes which cannot be discussed herein.

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Executive Summary

Overview

Thirty years ago the vision of directed energy weapons, using high energy lasers (HEL) and high power microwaves (HPM), was first seriously engaged by the military. Within a decade the capability of these weapons to destroy or disable targets had been proven, and numerous demonstrations of lethal effect, on increasingly difficult targets, have been carried out since then. The technology needed to implement these weapons in compact packages suitable for integration on combat platforms was lacking in the beginning of this campaign, but is now coming to maturity. Numerous advances, some of them dramatic and even revolutionary, have been made in types of laser devices, device efficiency, prime power generators, thermal management, beam control, sensor and control electronics, optics and antennas, and materials. Collectively these advances open the door to directed energy weapons that not only match the initial vision, but in some cases far exceed it. The Air Force applications of directed energy weapons technology that can be brought to demonstration over the next three decades are shown in the following table.

high	**Airborne Laser Space Control**	**Aircraft Defense UAV-TMD Medium Range HPM**	**FotoFighter GPOW* Virtual Presence**
Payoffs med	**IRCM Ballistic Winds Satellite Imaging Short Range HPM Space Based Laser**		
low	**Power Beaming**	**Space Debris Clearing**	
	10 years	**20 years**	**30 years**

Time for Prototype Development

Figure 1 Air Force Applications of Directed Energy
*(*GPOW: Global Precision Optical Weapon)*

The major impacts of directed energy weapons on Air Force missions over the next three decades will include the defense of aircraft against antiaircraft missiles and boost phase defense against ballistic missiles, carried out initially by airborne weapons and later by high-altitude UAVs and space based or space relayed weapons. In mature form, space based or space relayed weapons will provide real time global engagement capability, with revolutionary implications on the nature of warfare.

Projections for this thirty year period have been grouped into three 10 year categories. These are not rigid time frames; they are estimates of what could be accomplished if a suitable effort is undertaken. The applications shown in the first decade are based on technology that is in hand, or nearly so. Engineering development is needed to bring these applications into reality. Applications in the second decade are those for which the supporting technology can be clearly extrapolated from research and development currently in progress and can therefore be proposed with a good degree of confidence. The third decade applications are more visionary; they are based on technologies that are possible in principle, but not yet demonstrated in ongoing R&D programs. These visionary applications have extraordinary impact on the future of the Air Force, and thus are the motivation for some of the key R&D recommendations in this report.

The Airborne Laser (ABL), developed as a boost phase theater missile defense weapon, will probably be the first practical and effective heavy duty directed energy weapon to be deployed. It represents the culmination of technology developments to the present and it will be the flagship demonstration in the first decade. The ABL draws upon recent advances in adaptive optics and atmospheric turbulence compensation. Other first decade HEL applications that exploit these technologies are ground and air based anti-satellite weapons (ASAT), satellite imaging, and power beaming. Aircraft will derive improved survivability against increasingly sophisticated antiaircraft missiles from the progressive application of lasers in countermeasure or antimissile roles. The first decade should see lasers deployed, initially, for the purpose of logic jamming advanced missile seekers that have flare rejection features. Later in the decade, as seekers with focal plane arrays and robust antijam features appear in inventories, lasers capable of destroying or disabling such sensors should be ready for use. These aircraft defensive systems will be outgrowths of current development programs in compact, low-to-mid power IR lasers, passive IR threat acquisition and tracking sensors, and precision beam directors. Finally, new developments in compact power supplies, techniques for thermal management, and antenna design will enable the demonstration and deployment of high power microwave (HPM) transmitters for jamming or disabling electronic systems at short to moderate ranges.

The second 10 year period is expected to see the deployment of more advanced versions of aircraft defense against missile attack (A/C defense) made possible by the steady progress in both HEL and HPM technology. Laser weapons capable of burning into missile airframes to destroy guidance electronics and other vital components will provide defense against both IR and radar guided missiles. These weapons will come in at least two sizes: (1) compact weapons, constituting only a small fraction of the aircraft payload, for short range self defense, and (2) medium range weapons, constituting the primary payload, employed for escort defense. Compact, high power solid state laser technology will be the key technical development underlying the aircraft defense applications, and that technology will also be employed in UAV mounted TMD weapons. UAV based TMD weapons will be similar to the medium range aircraft defense weapons, but more compact and carrying a smaller magazine. Continuing developments in HPM supporting technologies (e.g. compact pulsed power, antenna design, fratricide suppression) will extend the effective range of HPM weapons against electronic systems, adding dimension and robustness to aircraft self defense. These developments provide the rationale for another set of R&D recommendations. Adaptive optics and turbulence compensation technology, together with advances in high pulse energy, short wavelength laser technology will make

possible ground based systems effective in clearing space debris in this time frame, if they are needed.

The applications forecast for the final 30 year category represent dramatic extensions of DEW capability, based on ideas that are conceptually sound but that require technical developments in new directions. These applications will introduce major shifts in Air Force attack and defense strategies. Conformal arrays of phased high power diode lasers arranged on the surfaces of advanced aircraft (FotoFighter) are proposed to provide simultaneous surveillance, tracking, designation, and thermal kill of targets, as well as communication. Space based (GPOW) or space relayed weapons (Virtual Presence), once the full potential of modern and emerging technology is incorporated, will move beyond their initially motivating role of boost phase defense to a multitude of combat activities that have the potential to dramatically change the character of warfare. Global presence with weapons capable of destroying or disabling anything that flies in the air or in space, or anything on the ground or on the surface of the sea that is unprotected by armor, will drive a new warfare paradigm - a paradigm in which the primary imperative of warfare is to control space, and in which space becomes a major combat arena. In that new paradigm the very weapons that drive it will become threatened by their own kind, and the eternal measure-countermeasure contest will be renewed with new dimensions of technology and tactics.

The Function of Directed Energy Weapons

The function of a directed energy weapon is to place on a target sufficient fluence (joules/ cm^2) or irradiance (watts/cm^2) to inflict lethal damage or disabling disruption to critical components. HEL and HPM weapons act through different mechanisms, have distinct advantages and disadvantages, and are largely complementary to each other. HEL weapons have much shorter wavelengths and generate much narrower beams than HPM weapons. A HEL weapon irradiates a selected spot on a single target with high precision, and inflicts heavy damage on that spot; an HPM weapon attacks over a larger area that may include more than one target, and inflicts more subtle damage on electronic components. HEL weapons must be precisely aimed and pointed at the selected susceptible area of the target; HPM weapons need only be directed generally toward the target. HEL weapons do not operate through clouds while HPM weapons are largely unaffected by clouds. HEL weapons act through a thermal effect to heat, melt, or vaporize the narrowly targeted area; HPM weapons generate over the whole target high electric fields which couple inside through various openings and disrupt or destroy sensitive electronic components. Consequently, hardening against HPM weapons is not effective against and HEL threat, and vice versa.

Target fluence is the critical lethal parameter for HEL weapons. Against missiles and most surface and air targets HEL weapons act in the domain of less than one kJ/cm^2 to more than ten kJ/cm^2, usually delivered at an irradiance in the range of 100 to 10,000 watts/cm^2, over spot sizes of one to several tens of centimeters. The spot size is a critical factor in HEL weapons, since the laser energy required for a kill is roughly proportional to the area of the irradiated spot. Irradiating the smallest area that will yield lethal effect is the key to achieving weapons that are energy efficient and consequently compact. Weapon designs that are capable of delivering much tighter beams on target are critical to solving the size/weight problems that have inhibited HEL acceptance in the past.

Satellites are somewhat softer to thermal attack than missiles and typical air or surface targets, and they have long exposure times that permit low irradiance attacks. HEL antisatellite scenarios typically call for irradiance levels in the one to ten watts/cm^2 range, and target fluences of hundreds of joules/cm^2.

A special case of HEL weapons targets imaging sensors, which are uniquely susceptible to radiation attack within their operating bandwidth and field-of-view. IR detectors as used in FLIRs and missile seekers are susceptible to aperture fluences of 10^{-4} to 10^{-2} joules/cm^2. Broader sensor classes widen this range to aperture fluences of 10^{-4} to 1 joules/cm^2. For single sensor element scanning sensors, such as current missile seekers, the key issue is not damaging fluence, but access to the seeker. A properly timed attack will disable the sensor at modest laser fluences. Laser damage is in fact complementary to laser jamming for this class of sensors; sensor hardening against one approach will cause increased vulnerability to the other approach. For sensors with focal plane detector arrays, which are the emerging next generation of sensors, the vulnerabilities and hardening measures and results both for jamming and damaging modes of seeker defeat are highly important but virtually unexplored areas.

Target irradiance is the critical parameter for HPM weapons. HPM weapons operate in the domain of one to several tens of watts/cm^2 (one watt/cm^2 generates an electric field of 19 volts/cm, and the field scales as the square root of the irradiance), with fluence a small fraction of a microjoule/cm^2; they typically irradiate an area tens to hundreds of meters in extent.

Attributes of Directed Energy Weapons

The core attribute of directed energy weapons is a short time of flight to a target; they transit the distance to the target at the speed of light, which is about mach one million. This is a critical consideration in time urgent engagements or long-range engagements where the target exposure time is brief compared to the flyout time of conventional weapons. Other attributes are: (1) freedom from gravitational limits, Newtonian laws, and aerodynamic forces, which constrain the design of conventional weapons and limit their performance envelopes and engagement kinematics; (2) flexible engagement protocol-damage levels varying from functional disablement to lethal destruction can be inflicted on the target depending on the transmitted power and the irradiation time; (3) low expended mass per engagement, which translates into a deep magazine; (4) low cost per engagement, which permits free use in training and testing.

Numerous engagement scenarios illustrate the importance of time of flight. In self-defense and escort defense scenarios against rapidly closing missiles, the pointing agility of the DEW and the near-instantaneous deposition of energy permits defense under stressing timelines. Rapid destruction of a threat missile, accomplished with high target irradiance, permits multiple simultaneous threats to be engaged in quick sequence. In the theater missile defense scenarios, the Airborne Laser (ABL) and a Space-based Laser (SBL) can deliver the destructive fluence in a time very short compared to the total timeline for the engagement. They are both motivated by the need to destroy ballistic missiles in the boost phase, before those missiles can release large numbers of chemical or biological submunitions that would saturate midcourse and terminal defensive systems. The boost phase is brief; stressing case scenarios have engagement windows of several tens of seconds and interceptor missiles are hard pressed to reach far enough in that window to offer adequate battlefield coverage. The ABL, operating in-theater with a range of about 450 km, puts a beam on target within 1.5 milliseconds of firing; the SBL,

operating from space at ranges up to 4500 km, hits the target in 15 milliseconds. At those maximum ranges the ABL must continue firing for ten seconds to deliver a lethal fluence, and the SBL must fire for 15 seconds; the engagement window comfortably allows this firing time. Firing time drops off roughly as the square of the range.

The SBL and the ABL are motivated by the urgent and compelling need for boost phase defense. They are designed around current technology and are large and expensive. The SBL may be premature, even given the mission urgency. As presently conceived it would carry a stringently limited magazine of engagements and the cost per engagement would be very high. The ABL also carries a limited number of engagements aloft, but will be replenished for each sortie and the cost per engagement is rationally bounded. The ABL will probably be the first practical and effective directed energy weapon to be deployed.

Energy Frugal Kill

An effective laser weapon should maximize energy efficiency by delivering on target a beam matched to the required damage area. The beam area increases as the square of the range, or faster, and in long-range engagements the beam size at the target is often considerably larger than is needed. The fluence (J/cm2) required for lethal effect does not decrease significantly with the increased area, so the energy invested in the kill is excessive. As an example, current SBL concepts invest more than 100 megajoules in a maximum range kill, compared to about one megajoule required for a properly sized beam. This profligate expenditure of energy is a consequence of a laser beam on target that is ten times larger in diameter than is needed, or one hundred times larger in area. The excessive beam diameter is not a matter of choice; it results from technical limitations on the size of the optics in the beam director, together with the relatively long wavelength of the laser and the imperfect quality of the laser beam.

Innovative Technologies and Practical Laser Weapons

Many of the laser weapon conceptualizations in the past have involved unacceptable size and weight penalties driven by excessive spot size on target. For the future we see innovative technologies that will support laser weapon designs better optimized for the mission requirements: (1) large, lightweight optics and HPM antennas using thin membrane fabrication; (2) high power short wavelength solid state lasers; (3) high average power phase conjugation to achieve automatic beam aiming and good beam quality in optically distorted media; (4) new approaches to adaptive optics based on adaptations of various types of light valve technology, or using microelectromechanical devices grown on chips; and (5) phased arrays of diode lasers for beam shaping and control.

Of the five advanced technologies listed above, membrane fabrication for large optics an antennas is the newest and most speculative. The other four advanced technologies involve major extrapolations or radical adaptations of current capabilities and are the subjects of on-going R&D.

The prospect of thin membrane optics and antennas has been a subject of speculation for many years, but the difficulty of achieving near diffraction limited performance has inhibited serious development (small examples have been built). However, the rapidly maturing technologies of adaptive optics and phase conjugation should be capable of extracting diffraction

limited operation from imperfectly shaped thin membrane optical elements, and optically based figure monitoring techniques together with wavefront compensation at the secondary level should permit HPM transmission with minimum divergence. Membrane optics and antennas would be inflated structures, with electrostatic forces possibly employed for shape modification. Thin membrane technology will be most applicable to space systems, because of the absence of gravitational distortion and aerodynamic forces. (However, this is not to rule out large ground based systems.)

The vision for space membrane structures extends to 20 meter diameter mirrors and one to ten kilometer diameter microwave antennas. Twenty meter optics, together with one micron laser wavelength and a diffraction limited beam would produce an energy frugal space based weapon with a vastly expanded engagement capacity. One to ten kilometer microwave antennas would give space based HPM weapons the range needed to act effectively against surface and air targets, and bring to the space warfare scene all weather capability. Space based HPM weapons also offer the option of non-lethal disabling of targets, and the operational flexibility that is implied by that capability.

NASA needs giant space optics for its search for planets in other star systems, and the military needs them for high performance laser weapons. The time has arrived to engage the membrane optics and antennas concept in a serious way.

An alternative to basing lasers in space is to base the laser on the ground and relay the beam off space based mirrors to deliver it to the target. Laser Guidestar technology for atmospheric compensation allows a ground telescope site to view a scene or irradiate a target anywhere around the globe while a relay mirror is in a position to provide the view. This approach will also benefit greatly from the ability to deploy giant optical systems in space. As contrasted with space basing for the laser, a ground/relay approach places all the heavy and complex hardware on the ground so that the laser can be routinely maintained and fueled; however, the beam must be propagated upward through the atmosphere, which introduces the complexities of atmospheric compensation and the outages imposed by cloud cover. Great progress has been made in the past decade using advanced wavefront sensors and phase conjugate adaptive optics to measure the distortions of the atmosphere and to compensate for these degradations, making atmospheric compensation a near-term reality.

Such systems, with the laser based either on the ground or in space, begins to give new meaning to the concept of Global Presence. In addition to attacking targets and imaging at high resolution, low power lasers can be projected for battlefield illumination or for target designation; point-to-point or point-to-area high bandwidth communications can be carried out, low power laser beams can be used for downed pilot location, and optical IFF can be exercised; lasers of various wavelengths can be employed for active remote sensing of chemical or biological agents. We call this concept for an ensemble of global scale remote sensing and communications "Virtual Presence".

Adaptive optics and phase conjugation are two technologies that figure centrally in some of the present and most of the future applications of directed energy. These technologies have been demonstrated to produce near perfect beams or images in the presence of major optical distortions. They can remove the effects of path turbulence or figure imperfections in optical elements. They permit the use of light weight, cheap, imperfectly figured optical components,

such as the space based membrane optics described above, and will open the door to major weight savings in beam directors for airborne laser weapons. They have been used to correct the distortions in lasers themselves, distortions that otherwise build rapidly as the lasers are operated at higher power levels. Major advances in these already demonstrated technologies are needed: phase conjugation must be extended to operation at high average power, and adaptive optics needs an implementation that is inexpensive and readily extends to large numbers of adaptive elements. Concepts exist for both of these needed advances. Phase conjugation, which has been mostly based on stimulated Brillouin scattering (SBS) thus far, can be implemented using stimulated thermal scattering (STS) - another Russian invention. SBS is difficult to apply at high average power; it prefers high peak power short pulse operation, and high average power implementations are awkwardly large. STS is a surface scattering phenomenon that is innately compact and should work best in high average power systems. Alternative implementations of adaptive optics may employ either "light valve" technology or microelectromechanical fabrication techniques, either one of which should inexpensively yield thousands, or even hundreds of thousands of adaptive elements, with high bandwidth response as a bonus.

Diode pumped solid state lasers (DPSSLs) are relative newcomers on the laser evolutionary ladder. Diode pumping is much more efficient than flashlamp pumping, which is the traditional method of exciting solid state lasers, and it results in much less heating of the laser as well. Technical advances in diode array fabrication and cooling have been made, and these have motivated the rapid development of DPSSLs up to the kilowatt average power level. There are no apparent technical limitations to DPSSL power level. However, major reductions in the cost of diode arrays is needed to permit affordable extension of DPSSL power into the multikilowatt and megawatt ranges. It is likely that cost reductions will occur progressively, based both on increased scale of production and on improved diode designs and manufacturing technology. A factor of ten cost reduction is projected over the next decade, and on that is based the forecast of aircraft defense weapons in the twenty year time frame. A factor of fifty to one hundred cost reduction in fifteen to twenty years seems plausible, and on that is based the forecast of megawatt scale UAV based boost phase weapons for TMD in the twenty year time frame and megawatt scale GPOW weapons in the thirty year time frame.

The defense of aircraft against missile attack is a particularly vital application of HEL and HPM technology. Aircraft defense can be conducted at relatively short range - a factor conducive to compact directed energy weapon design. HEL weapons will probably evolve through four stages of capability: (1) infrared logic jammers (fractions of a watt); (2) infrared antisensor weapons capable of destroying IR sensors (tens of watts); (3) short range heavy duty weapons capable of destroying IR or radar guided missiles in self defense scenarios (tens of kilowatts); (4) medium range heavy duty weapons capable of destroying IR or radar guided missiles in escort defense scenarios (megawatt class). Steps (3) and (4) require diode cost reduction. A necessary concomitant to laser weapons is a threat detection and tracking system capable of locating the incoming missiles with good angular precision. Either passive infrared arrays or active microwave arrays appear capable of providing this capability.

DPSSLs with low cost diode arrays will also be employed in the UAV based TMD weapon. This weapon will be much more compact and less expensive than the ABL, but it will have shorter lethal range and a smaller magazine. It will have a long on-station loiter time. Flying at high altitude and engaging at shorter range, the UAV weapon will encounter a much reduced

atmospheric distortion problem and will operate without the sophisticated atmospheric compensation needed in the ABL. Being unmanned and relatively inexpensive it will be attritable, and it will be forward based over suspected TMD launch areas where its reduced engagement range will still be effective.

Particular advantages of using HPM weapons in A/C defense are (1) all-weather operation, and (2) greatly reduced target pointing and tracking requirements. The relatively close range accommodated for A/C defense (~1 km) allows modest power supplies, power conditioning, and antenna packaging. The evolution of HPM weapons will probably progress from (1) electronic interrupt precluding missile closure, (2) electronic component burnout causing permanent damage, to (3) potentially catastrophic kills involving warhead detonation out of harms way. The latter is particularly attractive in that kill assessment is straightforward. Particular engineering attention will need to be given to fratricide and suicide of other A/C electronic components and subsystems. Recent experiments suggest that survival of one's own assets is possible. Fruition of this technology to robust application is very likely within two decades.

Diode lasers can be employed to great advantage in pumping solid state lasers, but even greater leverage can be gained if the diodes can be employed directly as weapons. Single diodes are low power devices, however, and weapon scale operation requires that large numbers of diodes be combined in an active phased array. Such arrays have been demonstrated at low power and concepts that will extend to high power are under study and development. Because of the inherent high efficiency, wavelength diversity, and ruggedness of laser diodes, choherent diode laser arrays, if proven scalable to high powers, will be the laser of choice for virtually every laser application of the future in which the diodes meet the wavelength requirements.

The concept of laser systems, configured as large arrays of diode lasers, leads to an interesting implementation for aircraft self-defense, dubbed "FotoFighter". Wafers of laser diodes and imbedded sensors would be fitted conformally to the surfaces of an advanced aircraft. The laser "patches" would be addressed electronically, generating varying powers for communication, designation, and for thermal kill of a target, and would be steered electronically. The integrated sensors provide for closed-loop tracking and for phase compensation of atmospherically induced degradations as required. Because they are microelectronics based, they can be mass-produced, promising low cost through economy of scale. The reliability and lifetime of laser diodes is well proven (in CD players and CD ROMs), and the large arrays would degrade gracefully with the failure of individual diodes.

Other DEW Applications

There are two additional applications of HEL technology that may or may not emerge to importance in future years: (1) the use of ground based lasers to clean up space debris, and (2) the use of ground based lasers to beam power up to rockets, satellites or to high altitude loitering platforms.

The need to clear space debris is not yet compelling, although it could become so, and whether or not it would be an Air Force task is an open question. The problem arises with debris in the size range from one to ten centimeters. Debris larger than one cm is very difficult to shield against, and debris smaller than 10 cm is too numerous and too difficult to track with radar to employ an avoidance strategy. The idea of a laser sweep is based on the impulse that a pulsed

laser can deliver to a target. A short pulse laser with sufficient fluence will vaporize surface material; the vapor coming off at high speed (at about the speed of sound in the target material) transfers momentum to the target. Debris in low earth orbit, if slowed by about 200 m/sec, will drop low enough in perigee to encounter the upper atmosphere and be quickly removed from orbit and burned up on reentry. Preliminary calculations suggest that a modest laser (20 kJ per pulse, 40 nsec pulse width, one pulse per second, at 0.53 mm wavelength - which has already been built for other purposes) would deliver the necessary impulse with about one hundred pulses, and that clearing the LEO debris field could be accomplished in several years of operation. A sophisticated laser illuminator-electrooptical sensor-computer processor scheme has been proposed to locate and track the debris.

Laser power beaming has been proposed in several different contexts: (1) providing power to communications satellites during their passage through the earth's shadow, a function currently provided by batteries that have limited cycle life; (2) providing power to high altitude UAVs or balloons for both propulsion and payload uses (communications, radar); (3) energizing the propulsive mass for rocket engines, during lift-off from earth, or for orbit raising, and even for long range interplanetary travel; (4) powering manned stations on the moon during the lunar night. Lasers could probably be applied to these needs, but it is not yet evident that they are the preferred, or even a practical approach; laser energy is expensive.

Summary

The major impact of directed energy weapons in Air Force missions over the next three decades will be in the defense of aircraft against antiaircraft missiles and in boost phase defense against ballistic missiles, carried out initially by airborne weapons and later by space based or space relayed weapons. Space based or space relayed weapons, once the full potential of modern and emerging technology is incorporated, will move beyond their initially motivating role of boost phase defense to a multitude of combat activities that have the potential to dramatically change the character of warfare. Global presence with weapons capable of destroying or disabling anything that flies, in the air or in space, or anything on the ground or on the surface of the sea that is unprotected by armor, will drive a new warfare paradigm. In that new paradigm the very weapons that drive it will become threatened by their own kind, and the eternal measure-countermeasure contest will be renewed with new dimensions of technology and tactics.

Directed energy weapons have lingered on the fringes of military acceptability for three decades, a bright promise, anticipated by many and well understood by some, but impeded by technical limitations. Innovative technology of revolutionary impact on warfare has often lingered long on the fringes while it matured to practical utility. As an illustration: gun technology in the western world emerged in the mid-thirteenth century (Roger Bacon, 1242), but did not mature enough to change the character of combat until the mid fifteenth century, in the form of artillery (Constantinople, 1453), and the early seventeenth century, in the form of muskets (Breitenfeld, 1631). The pace is faster now. The technologies for directed energy weapons have expanded vastly and are maturing rapidly; they are nearing the critical transition point. Major engineering advances have been made in the form of improved laser material, new wavelengths, high efficiency, thermal management, optical materials and components, sensors, and computer processors. Radical innovations (miracles) have been introduced in the form of adaptive optics (American), phase conjugation (Russian), diode pumping of lasers (American), and

microchannel cooling (American), among others. These radical innovations have been developed and tested sufficiently to project their feasibility, application, and impact. An innovation new on the scene, of major importance but not yet tested, is thin membrane optics, which opens the door to very long range energy efficient weapons and to major weight reductions in moderate range weapons. This innovation should be exploited with the highest priority.

Many of the technologies and capabilities incorporated into directed energy weapons have applicability to other systems and missions. Indeed, some of the directed energy technologies and capabilities are derived from other sources. The ability of a directed energy weapon to attack a target over a small, precisely selected spot at long range carries with it the capability to find, image, precisely localize, and identify that target for whatever other purpose may serve military needs - intelligence assessment, communication, or designation or illumination to support attack by conventional weapons. It is even possible that directed energy weapons technology will be applicable to secondary roles such as power beaming or space debris clearing, although that remains to be determined.

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Illustrations

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1.0 Introduction

Man has long been intrigued with the notion of projecting energy at the speed of light in the pursuit of warfare. Archimedes' defense of Syracuse in ancient Greece by reflecting sunlight from hundreds of hand-held shields to set afire the invading Roman fleet, even if only a myth, makes the point. In modern times the invention of the laser and the klystron within the past several decades has inspired considerable expense in the pursuit of directed energy weapons (DEW) overwhelmingly in two forms: high energy lasers (HEL) and high power microwaves (HPM). The results of that R&D effort have been disappointing to some in that no DEW system has yet been inventoried. On the other hand a large body of experiments and demonstrations have resulted in an enormous and mature technology baseline which now allow us to make much more accurate predictions about the technology which is and will be available in the foreseeable decades for military applications. This volume discusses that future.

We first discuss potential applications of both HEL and HPM in three time periods - 10, 20, and 30 years. An application must be demonstrated in prototype to fit within a given decade. These projections are based on technology only and obviously do not reflect programmatic commitments or operational requirements. Furthermore not all potential applications have been listed - such a list would be very long. Over one hundred such applications were identified in a recent Laser Mission Study for lasers alone. Rather we discuss those applications which in our view make the largest contribution to airpower in the projected time periods. These applications are discussed in Section 2.

Next we discuss relevant technologies in Section 3. These are the technologies which in general will be required to enable the applications previously discussed in the 20 and 30 time periods. Technology for 10-year applications must be known today. Finally we present the conclusions and recommendations that we have developed during the course of this study.

2.0 Applications

"10 -Year" Applications

2.1 Airborne Laser for Theater Missile Defense

The Airborne Laser (ABL) projects laser radiation to tactical ballistic missiles, using thermal energy to produce catastrophic damage to threats within lethal range. The Airborne Laser has the primary mission to support theater missile defense using integrated optical technologies to provide speed-of-light capability to destroy theater ballistic missiles during boost phase at long range. The inherent advantages of this weapon concept are: it destroys the missile during boost phase when it is highly vulnerable and can be easily detected and tracked; it engages the missile prior to any release of submunitions; and debris resulting from missile destruction may fall back on enemy territory. The ABL is a highly mobile platform and provides unique employment flexibility not available with land-based systems. The system is designed to enter the theater ready-to-fight and operate in friendly airspace a considerable distance from the battle area. Along with other high value airborne assets in the theater, it is supported by defensive aircraft to enhance survivability. In addition, the ABL has demonstrated self-defense capabilities. The high altitude airborne laser system with a primary mission of Theater Missile Defense can also be deployed for large-area counter air mission. The system can enforce a large no-fly zone at high altitudes against threat aircraft, cruise missiles, and surface-to-air missiles. At lower altitudes the ABL can enforce a moderate size no-fly zone when there is a cloud-free line of sight.

The Airborne Laser technology program is responsive to Air Force requirements to attain boost-phase intercept capability to complement an Air Force counterforce capability against tactical ballistic missile (TBM) launchers. The operational requirements to which the ABL program responds are the TMD JMNS (approved by JROC - Nov 91), the Air Force TMD MNS (approved by VCSAF - Oct 91), the Air Force TMD CONOPS (approved by CSAF - Feb 93), and the ABL ORD (final draft - Oct 93). Based upon a strong statement of support from the commanders of Air Combat Command, Air Force Space Command, and Air Force Materiel Command, the technology program was transferred to the Air Force by BMDO in FY 92 along with TOA, augmented by Air Force funds to complete the technology risk-reduction program.

The ABL program has begun ABL concept designs to be completed in FY 97. The concept designs, being conducted by two competing industry teams, address the demonstrator system which will have traceability and scalability to a system with full operational capability as defined in the technical requirements document (TRD).

The contract teams are developing a top level concept description of the Fully Operational Capability (FOC) Aircraft which will have a lethality range of several hundred nautical miles (depending on the range and burn-out altitude of the missile). They are concurrently performing risk reduction experiments to support their specific design which coupled with the ongoing government Technology Insertion Program (TIP) will provide high confidence in the viability of their FOC design by downselect. They are then deriving from this FOC design a fully scalable and traceable ABL Demonstrator which will have a range about two thirds that of the FOC system. The ABL demonstrator will have a residual operational capability analogous to the use of JSTARS in Desert Storm. The most significant difference between the FOC and

Demonstrator is the laser power which will be approximately half. A single team will be selected in 1997 to complete the ABL Demonstrator. This team will be required to demonstrate a module (~10%) of their FOC laser at full power using flightweighted hardware by PDR (1998). This is the major risk reduction activity with regard to scaling the laser and is consistent with laser scaling strategies which have been utilized successfully in the past.

The aircraft is expected to be a modified widebody aircraft platform suitable for housing the ABL Weapon System. Analyses of existing aircraft indicate several candidates which can provide 6 hours endurance at altitudes of 40,000 to 45,000 ft while carrying 100,000 lb payload. The ABL aircraft will normally be based at an Air Force base in CONUS. When deployed to a theater of operations, ABL aircraft will not be dispersed, but will operate from an in-theater main operating base (MOB).

The ABL program includes a technology risk-reduction program which is demonstrating key optical technologies for long-range laser engagements, and weight reduction for aircraft installation and mission endurance. The work under the technology program reduces risk in areas of atmospheric characterization, atmospheric compensation and tracking, laser device performance, and vulnerability criteria. The technology work supports a demonstrator development program which integrates laser and optics on an airborne platform with the capability to engage realistic targets at realistic altitudes and ranges.

The technical risks will be addressed by a combined government-industry Integrated Product Team which are working to the same two exit criteria:

- Propagation and Lethality - Can we kill the target by focusing sufficient lethal energy under representative operational conditions?
  - Atmospheric considerations
  - Target vulnerability
  - Beam stability
- Aircraft Integration - Can we package a laser device and beam control system (beam quality, power, efficiency, etc.) in a militarily useful aircraft?

These exit criteria are to be quantified through the concept design process and continuing dialogue with the operational command. The award of the ABL Demonstrator contract, a major demonstrator resource decision point, will follow the delivery of the concept designs in early FY 97.

The technology program leverages a large number of accomplishments in Air Force, Army, Navy, and BMDO laser and optics projects. These date from the experience gained during the integration of the Airborne Laser Laboratory in the late 1970's to the recent demonstrations of low absorptivity coatings and precision tracking over very long ranges. The ABL program also leverages ground-based laser technology in the areas of atmospheric turbulence compensation and Chemical Oxygen Iodine Laser (COIL) performance.

The Airborne Laser operational scenarios introduced some specific technology issues which were defined in concert with BMDO in 1992 and which are now being addressed by the government-industry team. The major technical challenges are to:

- Characterize upper atmospheric turbulence including micro-meteorological and macro-meteorological effects
- Evaluate phase-only adaptive optics performance in the presence of scintillation
- Demonstrate active tracking through distributed turbulence
- Identify laser technology improvements leading to weight reduction
- Verify robust target damage modes
- Anchor codes used for design analysis and performance prediction

The Chemical Oxygen Iodine Laser (COIL) provides several unique advantages for the Airborne Laser (ABL). For a laser system in which the aperture diameter will be constrained by aircraft fuselage size, the COIL wavelength (1.3 mm) assures that diffraction will not limit the performance of the system at long ranges. The COIL system uses reactants which are stored and fed at near room temperature and modest pressures, facilitating handling in the field. Additionally, COIL has the potential for greatly reduced production costs due to easily-achieved tolerances in key components and the use of plastic parts throughout the device (which also contribute to weight reduction). These factors are only significant in the context of the impressive COIL performance achievements demonstrated at the Phillips Laboratory and in industry. COIL power scale-up, durability, reliability, and beam quality have been particularly successful among high-energy lasers developed in the US in that every laser performance goal since 1980 has been met within six months of the target date with full performance achieved within two months of first light. COIL technology developments have directly or indirectly resulted in lighter weight subsystems which, with the experiments underway in the ABL program, can meet the lethality, weight and volume requirements for the ABL operational system.

The ABL will require conventional phase-only adaptive optics for atmospheric compensation. By projecting a low-power laser beacon to the target and sensing the return, the optical distortions introduced by atmospheric turbulence can be measured at the ABL platform. The atmospheric distortions can then be corrected with a deformable mirror placed in the laser beam train. Key aspects of this technology are being used routinely at the Phillips Laboratory Starfire Optical Range and are being evaluated for the ABL at the MIT/Lincoln Laboratory Firepond facility using existing hardware in carefully scaled ground experiments. These experiments have achieved performance levels under stressing atmospheric conditions that meet ABL operational system requirements. Data analysis from airborne experiments flown in 1993 (ABLEX) provides confidence that this technology will meet the required optical performance for the ABL mission. Recently completed airborne experiments (ABLE ACE) will provide data for concept design contractors to optimize their adaptive optics point designs.

The weather factors of wind, rain, and clouds are not expected to result in any significant reduction in mission effectiveness for the ABL. The ABL will typically be flying above 40,000 feet, where cloud-free line-of-sight statistics indicate better than 90% probability of clear line-of-sight for mid-latitudes. Cloud-tops may occasionally rise above the aircraft altitude, but tactics and real-time aircraft repositioning can recover a favorable geometry. ABL's speed-of-light engagements and autonomous acquisition, tracking, and pointing systems will not require detection or acquisition of the targets below the clouds.

Jitter is introduced into the laser beam primarily from three sources: Platform base motion (aircraft vibration), tracker jitter (instabilities in tracking the target), and optical tilt induced by atmospheric turbulence. Track jitter and atmospheric turbulence tilt are reduced simultaneously through a closed loop control system using the beacon projected from the ABL to illuminate the target. Dynamic tracking experiments from ground and space-based platforms have exceeded the requirements for the ABL program. Engineering analysis has shown that these demonstrated technologies can be integrated into airborne systems that meet the ABL jitter requirements. The concept design efforts will provide the integrated system designs.

Compensation for rigid body aircraft base-motion is straightforward because the disturbance frequencies are low. These disturbances are easily rejected in the optical system by conventional dynamic steering mirrors. Aircraft vibration is rejected by the combination of precision stable reference units, passive isolation techniques, and the high bandwidth tracking and atmospheric compensation system required to remove the atmospheric turbulence effects. Component technologies have been demonstrated in each of these areas that meet the ABL requirements. Engineering and integrating these demonstrated technologies into the ABL system is an important element of the concept design phase.

The airborne laser for Theater Missile Defense (TMD) is currently funded through demonstrator development in the Air Force POM. The demonstrator program producing an ABL demonstrator with residual operational capability will be completed in FY 02. Adjunct missions, such as the counter air capability, would require an additional $70 million for sensor suite and optical system enhancements with an IOC of FY 02.

2.2 Infrared Countermeasures

The Concern

Infrared seeking missiles are a serious threat to all aircraft operations; in some scenarios they are the major threat. This is because of several characteristics which distinguish them from other threats such as anti-aircraft and RF guided missiles:

- They rely on totally passive means to acquire and track targets. The missiles present no signature before launch and after launch exhibit only an infrared exhaust plume.
- Many surface-to-air versions can readily be carried and operated by a single individual (so-called Manpads); they are cheap compared to aircraft and readily available internationally.
- Several nations have IR guided air-to-air missiles that are capable of tracking at large off-boresight angles and executing turns at up to ~ 30 g's. Against such missiles, maneuver, the traditional pilot's approach, is not effective.

The Present

Infrared missile seekers which have been deployed in the past have been designed around optical scanners or image dissectors and have used a single detector or an array of a few detectors. The simplest versions of these seekers determine the bearing of the target by measuring the time, during the scan, when a strong radiation source is picked up by the detector. This design

can be decoyed by ejecting flares, which are brighter sources of radiation than the aircraft itself. Flares constitute the main deployed defense against IR seeking missiles.

Another approach to confusing these simple image dissection seekers employs an intense, rapidly modulated IR source on the aircraft. The modulated source couples into the detector(s) at various times during the scan, and is perceived as a target that is jumping around in direction. The tracking logic behind the detector(s) cannot process this and the missile fails to lock on the target. This works against some, but not all, image dissection seekers.

In response to the use of flares, missile designers have deployed more sophisticated seekers which attempt to distinguish between flares and the real target. Temperature and speed are useful discriminants; the aircraft plume is a diffuse source with a temperature of ~ 600 degrees Celsius which moves with the aircraft; a flare is a much smaller and hotter source which rapidly slows to a terminal velocity on the order of 100 mph. For attacking fast moving aircraft, kinematic schemes have been employed to disregard the "targets" which are rapidly slowing down. Against modulated jammers and slow moving aircraft or helicopters, a multi-color scheme is generally favored. Multi-color processing makes use of the fact that the flares or jammers are much smaller than aircraft , and if they are to appear more intense than the aircraft, they must be hotter. The higher temperature source will have a higher ratio of short-to-long wavelength radiation than the cooler aircraft, and this difference can be processed to determine the true target.

The Immediate Future

While these improvements represent relatively minor technical advances in seekers, they exceed the countermeasure capabilities of flares and jammers, even of an advanced nature; at best they are being dealt with now by a mixture of tactics and flares.

One proposed class of solutions to the signature issue is to illuminate the seeker with laser radiation that provides the correct ratios of power in the bands that the seeker is processing, but of much greater intensity.

A laser countermeasure is more complex and costly than flares or modulated jammers; unlike flares or modulated jammers that radiate in all directions, lasers must be pointed at the target missile with some precision. Laser jammers incorporate three relatively sophisticated subsystems:

- A wide field of view sensor which detects the missile in flight and establishes a coarse (i.e.~ 1 degree resolution) track file for the missile;
- A high resolution pointer-tracker (~ 0.1 mrad - 1.0 mrad) which picks up the track from the coarse acquisition sensor and points the laser in the right direction:
- Lasers that radiate simultaneously in the proper bands and in the correct power ratios; the lasers must be modulated temporally to confuse the seeker processor and cause the missile to pursue a phantom target. (Since the laser is on the target aircraft, having the missile home on the laser is not the desired outcome.)

Much time and effort has gone into pursuing various schemes for jamming the missile into accepting a false heading; a feature which all approaches have in common is the use of off-axis

scattering and reflection (OSAR) from the seeker optics to get signal to the detector at a time when it is not looking at the aircraft.

There are disagreements between the proponents of various approaches which go by names such as open-loop or closed-loop jamming. In 1995 these may be important distinctions but in the 2005 time frame none of these techniques are likely to be useful against first- or second-world threats. This is because there are even more advanced seekers in the pipeline which will incorporate two capabilities that the current missiles lack; one is the use of staring infrared focal plane arrays and the others is the use of increasingly sophisticated computers on board anti-aircraft missiles.

Staring array seekers may strongly impact current deception jamming approaches. Such seekers detect the target aircraft constantly and do not determine target direction from the timing of detection pulses. Laser jammers will simply provide more signal to home on. (There is unresolved speculation as to whether a jamming effect might still be achieved against some focal plane designs by modulating the laser at the frequencies used in the electronic processing of the detector array, assuming those frequencies were known and predictable.)

Past deployed missiles used hard wired real time logic; if a tactic and/or flare deployment could beat the missile once, the same tactic/flare would continue to be effective until the missile hardware was modified. The most recent generation of missiles allows rapid firmware and/or software changes as well as more sophisticated track processing. As the electronics community projects ten-fold performance increases for every 3-4 years over the next decade at least; it is rational to expect processors beyond current Pentium or Power-PC CPU's in even very inexpensive manpads in the period beyond 2005. This could allow the missile to do considerable signal processing on the scene data.

IRCM in 2005

From the above discussion on trends in future missile seekers, it seems clear that the laser jammer will be effectively obsolete in the next decade. The most reasonable counter to increasing missile sensor sophistication is to abandon the logic jamming approach and undertake to destroy the missile sensors, i.e. to employ a laser or HPM anti-sensor device.

The measure-countermeasure evolution does not end with antisensor weapons. Concepts exist for sensor designs that are hardened against laser attack, and even for maintaining track during the attack. However, such damage resistant sensor concepts require technology that is still notional. Antisensor weapons should hold the advantage for a considerable period before they must be upgraded to heavy-duty structural kill weapons.

A laser antisensor weapon must transmit considerably more power than a jammer, but it is less constrained in spectral content and modulation than a jammer. The only spectral requirement is that it operate at any wavelength that is transmitted through the seeker optics to the focal plane. Simple prudence requires that the laser have some wavelength flexibility also, to preclude the effectiveness of simple line filters as a hardening response.

A critical factor in a laser antisensor weapon is the size of the beam delivered on target; smaller beams couple more irradiance and fluence into the seeker aperture and inflict greater

damage. Missile seekers employ imaging optics, which provides a retroreflection signal from an illuminating laser. This retroreflection can be employed to determine a precise, real time pointing direction for an antisensor weapon. This permits the use of a tight laser beam in the antisensor engagement. As an illustration, a low power 2 mm CW illuminating laser beam, pointed at the missile to an accuracy of 250 mrad, using the tracking data from a passive IR tracker, would generate a point-like retroreflection signal that would locate the seeker aperture to about 40 mrad, as viewed by a 10 cm receiver. The seeker tracking signal permits very high bandwidth (~500 Hz) tracking and pointing of the antisensor weapon, which in turn supports precise delivery of the laser beam into the seeker aperture regardless of missile maneuvers. A 2 mm weapon with a 10 cm beam director would deliver a 20 cm diameter beam on the seeker at a range of 5 km.

Seekers with focal plane array sensors will produce a steady retroreflection signal; any time the laser is fired it will produce damage on the focal plane. Seekers with an image dissecting reticle will yield a retroreflection signal that is modulated by the reticle; the reticle alternately intercepts the laser, absorbing some of the laser power and reflecting the rest, or transmits the laser on to the detector behind the reticle. The modulation information can be used to preferentially attack either the detector or the reticle.

Pulsed lasers of an energy of a few (~1-3) joules per pulse would appear adequate and could be made using various diode pumped solid state laser schemes.

With an HPM IRCM device, physical damage to the seeker or other missile electronics, or even catastrophic kill (e.g., detonation of propellant or high explosive) is possible at short range. At longer ranges (~ 1 km or greater) HPM will probably be limited to disrupting missile guidance or seeker electronics causing the missile to miss. An HPM device would not require the laser's fine resolution pointer-tracker; however, successful development of HPM for IRCM does require an increase in the levels of energy currently achievable, a reduction in the size and weight of the power sources, and a small efficient antenna that can be integrated into the aircraft.

In-band susceptibilities are best exploited by narrowband HPM sources tuned to the receiver's operating frequencies. Unfortunately, these frequencies are widely separated across the target types and are usually very high compared to optimal back-door coupling frequencies. In-band frequencies may not be known in advance for many threat missiles, although they may be measurable. A frequency-agile or wideband source would be required to take advantage of those measurements.

UWB would be a preferred approach since it minimizes the reliance on foreknowledge of threat missile characteristics. Current gallium arsenide bulk avalanche semiconductor switches are capable of 25 MW output, and potentially can be combined in a distributed phased array configuration. Gas switches are being developed for UWB sources that can currently produce 25 GW peak power output and will be improved over the next few years to produce up to 100 GW. Small high-power (~1 GW) impulse-radiating systems are being developed with a light-weight (100 lb) portable 1.6 m dish radiator that is expected to radiate a highly directional field approaching 1 kV/m at a distance of 1 km with a pulse width of ~100 psec. Improvements in these capabilities for HPM IRCM should be possible in the 2005 time frame.

Use of HPM for IRCM may require aircraft hardening to avoid suicide or fratricide, or else some systems may not be usable during the time the HPM device operates. While critical flight control systems have been found to be relatively hard to HPM effects, the hardness of all critical operational systems and subsystems should be assessed. New systems should be designed to enhance survivability in HPM environments.

Laser Antisensor Weapon: Weight and Volume Estimates in the 10 Year Time Frame

Laser jamming in one form or another is the approach being pursued in current activities of the Services and ARPA. The interested reader is referred to the *1994 SAB IRCM Study* for a discussion of these efforts. In looking to the future, ten years from now and beyond, antisensor lasers appear the next likely evolution in the missile protection area.

Less attention has been devoted to laser damagers than laser jammers but sufficient work has been done to establish several attractive features of scenarios for laser-induced sensor damage which are different than for jammers and which may considerably reduce the cost, in system weight and volume of pursuing this strategy. The major impact of these looser systems constraints is that both the illuminator laser and the jammer laser can be much more optimal devices. For example, a reasonable candidate for the illuminator could be a CW diode pumped Thulium laser or perhaps a single mode diode pumped Thulium doped glass fiber laser. Full scale 5-10 watt devices have operated in the laboratory at overall efficiencies of 10-20% and would have a total power budget of ~50 watts with temperature insensitive operation. The package size would also be small, ~0.1 cu ft and a few pounds.

The damager laser is not quite so well defined at this point but could notionally use copies of the illuminator laser to directly pump a 8.5 msec storage time Holmium laser at 1.93-1.95 μm. This choice would reduce the number of pump diodes and the heating by ten times compared to diode pumped Nd:YAG lasers. It should be possible to achieve ~ 30 watt laser powers, i.e. 1.5 joules per pulse at 20 Hz, with about 800 watts of prime power from a 0.5 cu foot package weighing ~30 lb including power conditioning. This latter factor is made possible by low voltage diode pumping at moderate currents where one should be able to switch from the aircraft bus and not use high peak power electrical storage, i.e. capacitor banks, because of the long laser lifetime.

The broad laser diode linewidth tolerance for end pumped operation, 780-790 nm, removes any restriction on coolant temperature for the diodes other than preventing catastrophic overheating above 55 C. The laser rod would require better stabilization but the heating load should be 3-5 watts so this is not a major item. Notionally a 10 lb ram air cooled air-to-water heat exchanger with some valves and plumbing are about right.

Both lasers should fit in a footprint of 0.7 cu ft and 50 lbs with less than 900 watts peak power consumption and 100 watts average power consumption with the illuminator operating.

Pointer/Tracker Issues:

The line-of-sight stability needed for a jammer is on the order of 250 microradians, while an energy frugal laser damager will require 40 microradian precision; irrespective of aircraft

roll. The stressing motion a pointer /tracker on a fast mover must cope with is shift of the optical line-of-sight caused by aircraft roll about the thrust axis because this can cause a line-of-sight rate shift of 150-180 degrees/second. The roll rate is substantially reduced for large aircraft to 20-30 degrees/sec.

These are not new issues. Coronet Prince, for example, was designed to cope with the more stressing case, the fast mover, and demonstrated overall LOS stability in the 50-100 microradian range some ten years ago. While this pointer/tracker met the performance goals, it was at substantial weight, on the order of 140 Kgms.

The much more recent and light weight (20 kg) ATIRCM tracker is designed more for moderate LOS rates, less than one radian/sec and is specified very loosely by the Army at a 3 milliradian pointing accuracy. Testing done by NRL on an ATIRCM pointer /tracker revealed a true capability to track at 100 microradians as long as a structural resonance at 68 Hz is not driven. Excitation of this resonance can lead to a 3 milliradian excursion of the tracking.

The most attractive direction for future development of pointer trackers is to use a lightweight approach and correct tracker and pointing with either non-linear phase conjugation or adaptive wavefront correctors. (The small beam size here, 10 cm, is similar to r_0, the lateral coherence length of the atmosphere and implies that a simple tip-tilt mirror is all the atmospheric correction needed.)

Conceptually, this could lead to devices of similar weight and volume to the ATIRCM tracker, ~20 kg and 0.12 cuft for laser damagers.

Summary:

With moderate attention to ensuring development of compact IRCM sources and trackers, system sizes of 100 lb and less than one cu ft total for an antisensor system should be practical in the 2005 time frame. These would be comparable to what should be achievable for laser jammers in the same time frame and may offer enhanced utility.

2.3 Ballistic Wind

Any object released or ejected from an aircraft into the atmosphere will be effected by the winds from the aircraft to the point of impact. This effect is called ballistic wind. There are at least three situations in which the effect can make a large difference in the impact point; 1) dropping gravity bombs or dispensers from medium to high altitudes, 2) dropping cargo, and 3) 105 mm shells from the gunship. The use of LIDAR in measuring ballistic wind has recently been studied largely as a result of analysis performed by the Laser Mission Study at the USAF Phillips Laboratory in 1992 and also the USAF SAB 1992 Summer Study on Global Reach/ Global Power. In essence the LIDAR beam is swept through the expected path of the object. Aerosols in the atmosphere moving at the velocity of the ambient wind reflect a portion of the beam to the receiver with a Doppler shift associated with the normal to the beam. From large numbers of these measurements all components of wind velocity may be determined, including updrafts and downdrafts. For most applications high precision is not required—errors of 10% or so taken even a few minutes before the object release appear to give satisfactory results. While the physics and mathematics of ballistic wind is now discussed in many reports, a particularly

useful summary appears in the Final Report of the SAB 1992 Summer Study "Concepts and Technologies to Support Global Reach-Global Power", Volume 3: Mobility Panel, pages 31-39.

In the intervening time since 1992 substantial analysis, design, and critical experiments have been performed. Probably the most important of these is a series of bomb drops from B-52s at high altitude with and without ballistic wind correction. In these experiments the LIDAR was operated from vans on the ground with the correction factor then provided to the aircraft. The improvement in bomb accuracy was remarkable (perhaps a factor of 5 or so) thus giving credibility to the technique. Currently another set of bomb drops are being measured with the LIDAR being airborne on a companion aircraft to the bomber. Additional experiments are being performed in geometries more appropriate to cargo aircraft and the gunship. While much remains to be done, it is clear at this point that one certainly can use LIDAR to measure ballistic wind sufficiently precise to make a substantial difference in many applications of importance to the USAF.

Concerning the future, even the near term of a decade, it would appear possible to remove ballistic wind error from USAF applications to whatever precision is required. With this information available the USAF should be able to predict the impact point of any object ejected from an aircraft — something that we cannot do today. The cost, complexity, weight, and volume of this system should be no more complex than other avionics systems given sufficient engineering and production.

2.4 Satellite Imaging

Technologies for imaging satellites emphasize high resolution in the optical wavelength regime (0.4 to 4.0 microns wavelength). The objective of ongoing research is to expand our understanding of new and innovative imaging modalities to image distant space objects through the earth's atmosphere.

High resolution imaging performance for space applications is partly limited by the size of the imaging optics; a decade of advances in optical fabrication techniques support the production of very large optical elements. Alternatively, one may employ sparse arrays of smaller aperture elements to achieve the desired performance, where each sub-element can be more economically manufactured using current optical fabrication technology. More significantly, when imaging through the earth's atmosphere, the limiting aperture is determined by atmospheric turbulence effects. In order to provide performance not limited by the atmosphere, imaging systems must operate in a manner which is insensitive to the random fluctuations of the viewing medium. A number of techniques (e.g., pre-detection phase compensation, Guidestar, coherent detection) have been developed for this purpose. For ground-based applications, these innovative techniques must be developed so that the achievable image resolution is determined by collecting aperture limitations and not the atmosphere.

The Guidestar solution to the problems of aberrations introduced by atmospheric turbulence uses an artificial "star" created by Rayleigh scattering of a reference laser beam in the upper atmosphere or by laser excitation of the atmospheric sodium layer. By recording the image of this reference beacon on a wavefront sensor, the atmospheric distortions can be

determined and then be canceled using a segmented or deformable corrective mirror in the imaging telescope. This technique is effective and has been successfully demonstrated by researchers at the Starfire Optical Range of the Phillips Laboratory.

An alternative to this technique is the use of narrow bandwidth laser light scattered from the illuminated target. Laser imaging techniques are based on the same principles as radar methods. Differences between the two, in terms of implementation and image products, are due to the much shorter wavelength of the optical regime. In general, the use of optical wavelengths for imaging and detection purposes leads to very high resolution measurements as opposed to wide field-of-view measurements. Laser techniques appear to be well suited for making angle-angle image, range and Doppler measurements.

The coherent properties of narrow band laser light provide the user with some unique sensing capabilities. For example, if coherent detection is used, then the laser returns can provide precise Doppler information associated with the target. As with radar, Doppler measurements provide measurements about a target's motion. Use of coherent light also allows the implementation of interferometric angle-angle imaging techniques that are relatively insensitive to near-field atmospheric turbulence such as that encountered when looking at an object in space from a ground telescope. In one technique, multiple laser illumination beams, sheared in the near field of the imaging detector, interfere at the target. Frequency shifts of a few MHz between each beam allow Fourier demodulation of the information provided by the sampling of the multiple near-field turbulent paths, enabling the computational cancellation of these atmospheric distortions in the collected data. The result is high resolution images without the inherent requirement of adaptive optics correction. A significant promise offered by coherent image detection is potential for lenless receiver arrays (simple intensity detectors), leading to the possibility of detector array scaling to size significantly beyond the apertures available in more conventional single aperture telescope receivers.

It appears possible to develop imaging techniques which are insensitive to optical path distortions in the atmosphere. Included in this class are speckle imaging and image reconstruction techniques such as sheared beam imaging. The basic procedure in sheared beam imaging (SBI) is contained in the method of speckle imaging in astronomy with a few subtle differences. The differences involve use of coherent light, temporal coding of independent illumination beams and light collection in the Fourier plane of the object rather than in the image plane. These differences basically provide a means of rapidly processing the received information to reconstruct an image of the object. The goal of both methods: astronomical speckle image reconstruction and SBI is to undo the phase perturbations of the atmosphere. This is accomplished by processing the autocorrelation of the image intensity in the transform plane for the astronomical imaging case and by encoding phase differences generated by the object onto the measurement plane for SBI. In some sense the method of forming an image in the SBI system is simpler than that of the speckle imaging construction.

Once imaging modalities insensitive to atmospheric effects are identified, one can apply sparse aperturing methods to synthesize even larger effective apertures limited only by the collecting array size. Synthesis of large optical systems using a modular approach offers great prospects for the fielding of ultra-high resolution imaging and extremely long-range surveillance systems. Since the imaging performance of the sparse aperture array is a function of the number of subelements in the array, the modular approach builds a "cost/performance

scalability" into the design. If manufacturing economies of scale can be realized, the unit cost of each subelement would be reduced and larger, higher performance systems could be fielded at lower cost/performance ratios than systems of lower performance levels. Manufacturing higher performance imaging systems of conventional (non-modular) design offer no such scale economies, especially when the total number of deployed systems is small. Also, modularity of the system design makes it possible to incrementally improve the performance of fielded systems by incorporating additional subaperture elements into the array configuration. This design flexibility allows one to improve the system performance as the need arises, or as additional funding for enhanced performance becomes available.

In aperture synthesis imaging, the optical field pattern is detected within the individual subarrays before image formation. The detected field pattern is then combined and manipulated by appropriate signal processing software to produce the composite image. As with the phased-array imaging approach, the resolution obtained in this fashion is characteristic of the size of the aperture array rather than any of the individual subaperture elements. In contrast to the phased-array imaging method, the aperture synthesis technique relies on specialized signal processing algorithms to reconstruct the desired image from the measured data, and does not require wavefront sensing, actuation, and control to form common focus images. Because the field measurements of the aperture synthesis technique are assembled and operated on in a computer, much more flexibility can be achieved in selecting the subaperture array size and geometry than in either the phased-array imaging technique or in conventional, non-modular designs. Furthermore, the freedom to employ image recovery through the use of flexible and relatively inexpensive signal processing techniques opens up many new possibilities for ultra-high resolution optical imaging. At the present time, Fourier phase retrieval appears to be a particularly promising image recovery scheme in atmospheric phase-cancelled imaging.

The objective of aperture synthesis imaging is to reduce the ultimate cost and complexity of the sensing elements required for ultra-high resolution imaging by relying in digital signal processing to perform the image recovery. While it is possible that some aperturing configurations for aperture synthesis may place a too heavy burden on the signal processing, it is believed that innovative aperturing schemes together with the appropriate measurement techniques can lead to elegant and efficient image recovery architectures.

2.5 Laser Power Beaming

Power can be beamed to a space object from the ground with a laser. Power beaming can assist orbit transfer (LEO to GEO) for both electric propulsion and for thermal (hydrogen) propulsion engines. These low-thrust, high Isp engines can be very lightweight using off-board power from a laser on the ground. Power for GEO repositioning and for station-keeping is especially appealing. Power transmission from the ground to satellites with a laser beam can extend the life of existing satellites by illuminating solar arrays while the satellites are in the earth's shadow, reducing degradations due to battery discharging. Power beaming may even eliminate batteries on some satellites and may be particularly attractive for high power consumption applications such as radar and HDTV.

The cost of moving payloads in orbit can be very high, greater than $5000 / lb. The costs are in the rocket and the additional mass of chemical fuel which must be carried, which may be four times the weight of the payload. Thermal propulsion, driven by a moderately high power

laser on the ground, can provide a lower cost alternative, although introducing a penalty in transit time: approximately 40 days for transfer to GEO for a thermal engine versus 1 day for transit for a chemical engine. Electrical engines have even lower thrust. Beaming power from the ground implies access to the orbital transfer vehicle from the ground stations during transit. For a representative mission scenario, of 40 day duration, 3 ground sites would be required. Each ground site would have a continuous wave laser of 400 kW power with a 4-meter beam director. The dwell time per site would be approximately 10% of the transit time. Subsequent analyses are looking at a point design which can achieve a 3-day transit time from LEO to GEO. Obviously, careful cost-benefit analyses are required to evaluate the payoff of power beaming for orbit transfer.

For power transmission, it is necessary to locate and track the satellite and to project the power precisely to the energy collector at the satellite. The collector is envisioned as a simple concentrator for the laser light which can focus the energy to the thermal thruster to heat hydrogen, the working fluid. Solar concentrators, coupled to a thermal engine have been built and tested by the Phillips Laboratory Rocket Propulsion Directorate, among others. The Phillips Laboratory experiment used a windowless heat exchanger cavity which is directly heated by the incoming solar energy. Propellant flows through rhenium tubing wound to create the cylindrical cavity and is heated. The tubing is connected to a rhenium thrust chamber through which the hydrogen is exhausted as supersonic flow. The solar concentrator provided 6 kW input thermal energy and the specific impulse achieved was 808 sec. The next step is to repeat the experiment with direct injection of the laser beam instead of the concentrated solar energy.

Projecting a laser beam efficiently from the ground requires compensation for atmospheric turbulence which causes beam spreading. Past demonstrations began around 1965 with the launch of several satellites with corner-cube retro-reflectors which could be used for tracking. At the time, the beam divergence was about 1 mradian resulting in only limited success. With turbulence compensation using the Guidestar technique, experiments were performed by a team consisting of personnel from the Air Force Phillips Laboratory's Starfire Optical Range (SOR), Sandia National Laboratories, and COMSAT which produced beams with much smaller divergences and a success rate of essentially 100%. The Guidestar technique uses a laser beacon, projected into the upper atmosphere to measure the turbulence-induced distortions, which can then be corrected with adaptive optics.

A ruby laser and a frequency-doubled YAG laser were used with the SOR beam director for these experiments. Several low-earth-orbit satellites with corner-cube retro-reflectors were illuminated at ranges from 1000 to 6000 km with a beam divergence estimated to be about 20 μradians. The return signal from the ruby laser showed rapid variations in intensity which may have been due to speckle effects. The return from the YAG showed that the satellite brightened by about a factor of 30 in the sunlight when the laser was turned on, and dimmed back to normal when the laser was turned off. The satellite was illuminated as it entered the earth's shadow and followed for about 10 seconds in the shadow.

Compensation for optical distortions is important to efficiently projecting the laser beam to the satellite. Beam control includes satellite acquisition, high accuracy tracking, higher order atmospheric compensation using adaptive optics, and precision point-ahead. Beam control may also include local laser beam clean-up with a low-order adaptive optics system. Much of this

technology has been demonstrated in experimental programs conducted for BMDO and the Air Force.

Another key technology for power beaming is a low-cost, long run-time laser which can be used to generate adequate powers in a high-quality beam. Several laser types are possible candidates, based on the requirement for long run times. Closed cycle flowing gas lasers, electric lasers such as the diode-pumped solid state laser, and nuclear pumped lasers could all be used. Because the laser is on the ground, the weight of thermal management and reactant supply can be accommodated to meet the long run-time need. The power required will vary from relatively low, for producing electrical energy at solar panels, to moderately high for providing power for propulsion.

The payoff of power beaming must be evaluated in the context of all the alternatives. For example, more efficient light-weight batteries which degrade less with cycling make the need for electrical power generated from a laser beam projected from the ground highly uncertain. Cheap propulsion for orbit transfer and station keeping may be an attractive application of laser technology which can draw on a relatively mature technology base.

2.6 Space Control

This section is included in the classified Appendix.

2.7 Active Denial

This section is included in the classified Appendix.

2.8 RF Gunship

This section is included in the classified Appendix.

2.9 Computers and HPM

This section is included in the classified Appendix.

"20 -Year" Applications

2.10 Aircraft Self Defense

Introduction

The major threat to US military aircraft over the next several decades is likely to be surface-to-air missiles (SAMs). Few, if any nations can afford to rival the US in terms of air combat capability, but sophisticated missile defense systems are available from various sources and can be proliferated even in third world nations.

SAM developments began during World War II, became a serious technical thrust in the 1950's, and emerged as the major threat to combat aircraft in the 1960's, during the War in Viet Nam. The air side of the equation responded to this growing threat along four avenues of development: (1) sensors and weapons specialized to detect and attack SAM launch sites,(2) tactics

to counter the effective employment of SAM systems and evasive maneuvers to elude the missiles in flight, (3) microwave and infrared countermeasures to degrade the missiles' ability to home on the target aircraft, and (4) stealth technology, to degrade the SAM radar's ability to detect and engage. In the three decades since the SAM threat became serious many technical and tactical evolutions have occurred on both sides of the measure-countermeasure exchange. However, aircraft response to a SAM in flight is still limited to evading or confusing the missile - frustrating the homing phase of the missile's attack. Missing from the equation is any capability by the aircraft to shoot back at an attacking missile, to destroy it.

A capability to shoot back against SAMs would be highly desirable. It would provide a robust defense, where by contrast the microwave and infrared countermeasures are always susceptible to defeat by the next development in sensors, processing, or logic. The inhibiting factor in shoot-back has been technical difficulty. The SAMs are small targets, very fast, and highly maneuverable; they are not easy to detect and localize in flight and they are difficult to hit with defensive gunfire or missiles. Laser weapons are quite capable of hitting the SAMs, but heretofore lasers with sufficient power to be lethal against the SAMs have been too heavy and bulky to be practically employed.

The thesis of this paper is that foreseeable technical advances in sensors and in lasers will, in the twenty-year time-frame, bring shoot-back into the picture as a practical and effective option for the defense of aircraft against SAMs. Laser weapons developed for that role will be effective also against air-to-air missiles and aircraft engaging within range of cannon fire.

The Vision

There are two major elements of this vision:

- The development of full-coverage infrared search and track (IRST) sensors capable of detecting missiles in flight, localizing and tracking them with good angular precision, and identifying the level of threat they present to the aircraft.
- The development of laser weapon systems capable of engaging and rapidly killing antiaircraft missiles at short ranges, and compact enough to be carried in fighter or strike aircraft without major reduction of the mission payload.

There are two alternatives to the laser weapon vision, which are:

- A more powerful weapon, capable of destroying antiaircraft missiles at longer ranges, constituting the primary payload of a combat aircraft, and providing local area defense for flights of several strike aircraft.
- A more powerful weapon, similar to the one described above, deployed as an "air-control gunship" at low altitude above a ground combat zone to provide the ground forces with a shield against tactical ground- and air-launched missiles.

Realizing the Vision: Threat Detection and Localization

The most likely technology that will emerge to provide the necessary threat detection, localization, and assessment is IRST. Development is already underway at the Naval Research Laboratory. The approach is to employ a number of compact staring IR detector arrays around

the airframe, to provide the necessary 4p steradian threat surveillance. The practicality of this approach is based on the steady reductions in the cost of staring arrays.

As an illustration, the threat warning system might be configured as follows. Fifteen to twenty arrays, each covering one steradian will yield full coverage. Each focal plane would be a 100 x 100 detector array, with each detector viewing a 10 mrad x 10 mrad field of view. The focal planes might have multiple filters to provide multispectral data for the purpose of threat identification.

Detecting missiles in flight is not the primary technical challenge; sorting the missiles out from the complex IR scene and achieving an acceptably low false alarm rate are the major problems. This requires fast computation. Frame-to-frame subtraction, to remove the static elements of the scene and leave only the moving elements, is complicated in this application by the motions of the aircraft itself, and by the fact that a missile closing on the aircraft via proportional navigation will present a fairly static image. The computer power needed for this task is available, and compact; the algorithms that will do the sorting and threat assessment do not appear to be trivial, but they are being developed and there is no reason to think that this will be a show stopper.

An alternative approach to threat detection and assessment that is still notional at this time is based on impulse radar. Recent developments in ultrafast pulse generation and detection at LLNL have led to the commercialization of very cheap, tiny transmitters and receivers that can detect and map (three dimensional mapping) objects at short ranges. This technology, micropower impulse radar (MIR), could conceivably be extended to higher power, or arrayed, to yield the detection ranges required for aircraft self defense.

Realizing the Vision: Laser Weapons

Several concepts must be brought together to develop a laser weapon that is both adequately lethal and sufficiently compact to be practical as an adjunct self defense weapon.

The size and weight of the laser weapon are strongly driven by the energy required to inflict lethal damage on the target, so the basic concept is to seek an energy frugal kill - to achieve lethal effect with minimum damage. This means attacking the target missile with a small diameter, but high irradiance (W/cm^2) laser beam and penetrating rapidly and deeply into the guidance sensor or the controls subsystem. This idea for killing missiles is not new; it has been demonstrated in several different laser weapon development programs. What is different is emerging technology that will permit the delivery of a much smaller, higher irradiance beam on target, and consequently a major reduction in the energy required for kill.

The table 1 shows the distinctions between the traditional laser-tactical missile engagement, as conceptualized and demonstrated in previous development programs, and an energy frugal self defense weapon.

Regarding energetics, the significant difference between these two approaches is a reduction of the beam size in the energy frugal approach by a factor of ten in diameter and a factor of one hundred in area. Compensating slightly for this is the larger lethal fluence assumed for the energy frugal approach. In net the lethal energy and the laser power required is reduced by a factor of 25 to 50.

Table 1. Comparison of traditional and energy frugal tactical laser weapon concepts.

	Traditional	**Energy Frugal**
beam dia on target	10-20 cm	1-2 cm
target irradiance	3 - 7 kW/cm^2	10 - 20 kW/cm^2
lethal fluence (assumed)	5 - 10 kJ/cm^2	10 - 20 kJ/cm^2
engagement time	0.7 - 1.5 sec	0.7 - 1 sec
lethal energy	0.5 - 2 MJ	20 - 40 kJ
laser power	0.5 - 1.5 MW	20 - 40 kW
engagement range	4 - 6 km	1 - 2 km
laser intensity	1 - 1.5 x 10^{15} W/Ω	2 - 4 x 10^{14} W/Ω
wavelength	3.8 or 10.6 μm	1.06 μm
beam director diameter	35-45 or 80-120 cm	15-25 cm
beam quality	2 - 3 x diff limit	1.1 - 1.3 x diff limit
tracking jitter	5 - 8 μrad	2 - 4 μrad

The small spot size which is critical to this approach results from two factors:

- A reduction in the engagement range by factor of three to four. This is a consequence of concentrating on the self defense role for the laser.
- A reduction of the beam divergence (beam quality times wavelength divided by beam director diameter) by another factor of three or four. This requires a short wavelength laser with good beam quality - an option which is only now emerging in the technology base.

The size and weight of the laser weapon will be greatly reduced by the very modest power and energy requirements, of course, but it is worth noting that a major reduction will also be realized by the small beam director that has been postulated. Reducing the beam director aperture by a factor of two will reduce its volume and weight by about a factor of eight, and the related air drag by a factor of four.

The emerging technologies that underlay the projection for a compact, medium power, short wavelength laser with high beam quality are:

- Diode pumping for short wavelength solid state lasers, which has demonstrated greatly improved efficiency (compared to the traditional flash lamp pumping)

and much reduced thermal load in the laser. In the twenty year timeframe, routine advances in this technology should yield a 60% diode efficiency and a 15% net electrical-to-laser efficiency. Diode costs should drop to below $1 per diode optical watt, and the cost of a diode pumping array for a 40 kW laser should be less than $160,000.

- Heat capacity operation of solid state lasers, which permits the lasers to develop increased output power as needed for short periods of engagement. Proper development of this approach should permit better than 500 J of laser output per cm^3 of laser material during an uncooled temperature run-up. At 40 kJ per engagement, and a ten engagement thermal magazine (400 kJ of laser output) the volume of laser material required would be 800 cm^3 and its mass would be less than 4 kg. (The mass of the laser material is only a small fraction of the laser system mass, of course.) Cooldown time between bursts of 10 engagements would be one to two minutes.
- Phase conjugation, either within the laser weapon or between the laser and the target to compensate for optical path distortions and produce a near diffraction limited beam. The lessons learned with the Airborne Laser (ABL), which is employing target-in-the-loop adaptive optics for atmospheric compensation, will be applicable here as well.
- Uncooled optics, which reduce the cost and weight of the beam director. Uncooled optics will be possible as a result of mirror coatings with ultra low absorption.

Lethality

The concept of attacking a missile with a small diameter (1 - 2 cm) beam and penetrating deeply is novel; the data base from laser lethality experiments emphasizes considerably larger beams and does not compass this situation. However, facilities exist in the US and in Russia that can conduct relevant experiments. The reason for expecting that such localized damage will be effective in aircraft self defense against missiles is that the terminal phase of the missile flight is normally very dynamic and high bandwidth control of the missile is required; damage to the sensor or guidance subsystems, combined with evasive maneuvers by the defending aircraft should be effective in defeating the terminal phase of the intercept. However, this expectation needs to be verified.

Other Applications

The laser weapon described here is not powerful enough to carry out the roles of strike escort defense or air-control gunship, which involve longer range engagements and many more targets. However, those roles permit the laser to be the primary payload of the aircraft and permit much larger systems. The diode pumped solid state laser technology should readily extend to the megawatt class, which these roles require. But it is unclear whether heat capacity operation can be extended far enough to handle the numbers of targets and their presentation rate. Invention, or alternative design concepts may be needed.

2.11 Ground Based Laser for Orbital Debris Removal

Problem Description

Orbital space debris can be produced by normal launch and mission operations, on-orbit spacecraft fragmentation, and on-orbit spacecraft or object deterioration. Other sources of material include spent launch stages and natural meteoroids and dust. There are an estimated 300,000 pieces of space debris in near Earth space >1 cm in size with strong density peaks in the 800-1000 km low earth orbit (LEO) band. Only 2% of these objects are presently catalogued by USSPACECOM. Space debris is becoming of much greater interest as the number of earth orbiting objects continues to grow. The population of the largest objects have grown at a rate of 3-5% per year and an average of four fragment producing on-orbit breakups occur each year.

Debris with sizes of > 10 cm can be monitored and tracked by ground-based radar and optical receivers allowing the possibility of avoidance by space vehicle maneuvering. Unfortunately, most vehicles are not equipped with the additional fuel that would be required for these evasive actions. Objects in the 1-10 cm size range, however, cannot be effectively tracked and have become sufficiently numerous to pose a potential threat to space assets since adequate mechanical shielding cannot be provided for projectiles over 1 cm in diameter. The level of damage inflicted depends upon the debris size, impact velocity, and spacecraft design but in a worst case the space asset would be destroyed, further contributing to the space debris population.

Laser-Based Debris Removal

A potential approach to the clearing of space debris in the 1-10 cm size range is the illumination of orbiting objects with high-energy laser pulses of short duration. The goal is not to thermally damage the debris in the manner normally invoked for a laser weapon target interactions. Instead, the high peak power resulting from pulses ~40 ns in duration generates an ablation jet on the surface of the object. When the debris is illuminated between the 30 and 45 degree ascending zenith angle, the resulting force component of this jet along the orbital trajectory causes deceleration and the outward component introduces orbital distortion and eccentricity. A velocity change of ~200 m/s is required to cause a decay of the perigee to <100 km after which re-entry is inevitable. For a general target, the laser interaction is distributed over multiple laser shots and passes.

A possible laser system for this proposed debris removal scheme is a frequency doubled Nd:glass laser. This conclusion is based on the extensive development of high pulse energy lasers for inertial confinement fusion (ICF) and good atmospheric transmission at 527 nm. It is estimated that using adaptive optics and a 6 m beam director, the required far field irradiance on target can be generated. For this beam diameter, 20 kJ delivered in a 40 ns pulse should provide low enough peak irradiance to suppress stimulated Raman scattering but is still short enough to generate the required irradiance on target. A second phenomenon which places an upper bound on the pulse duration is the growth of fine scale structure due to stimulated thermal Raleigh scattering. Under these irradiance conditions, an estimated 80-100 laser pulses would be required to de-orbit a 1 cm object and 800-1000 pulses for a 10 cm object.

An adaptive optical system using a laser guide star could provide the required < 2.5 x diffraction-limited divergence to target on which these estimates are based. An alternative and potentially more accurate technique to correct the atmospheric and beam director aberrations would be the use of a non-degenerate four wave mixing amplifier to phase conjugate a weak return from the debris object when illuminated by a low energy designator laser. Automatic fine pointing and tracking to the target would also result. A 40 ns pulse width falls into a regime in which stimulated Brillouin scattering (SBS) could very effectively provide the nonlinear mixing interaction. In either correction scheme, the optimal reduction in residual atmospheric absorption and aberration would be achieved by locating the site at as high an elevation as possible.

Target tracking sites distributed along the equator, also at maximum feasible altitudes, could operate automatically to provide debris ephemerides for laser engagements on multiple orbital passes. A worldwide network of tracking stations would constantly update and refine debris catalogs accumulating ephemeris data well ahead of target engagement. This data would then be handed off to an enhanced tracking laser system at the high power laser site. Very optimistic estimates of complete removal of objects 1-10 cm in diameters in a two year period.

The Debris Threat

Debris propagation and hazard models have been developed which simulate orbital debris cloud motion and determine the short term collision hazard posed to a satellite operating near a recently formed debris cloud. Predictions of future debris environments can be made by modeling known and anticipated debris source and sink terms. The initial results of these analyses yield a present probability of an encounter with a 1 cm or larger particle for a typical satellite in orbit for 1 year ranging from 0.00004 to 0.0004. It is estimated that projected environments for the most debris dense regions will not reach significant levels (1 loss per 100 years) for almost 100 years.

An important space debris mitigation strategy for the future will be to minimize unnecessary objects or to reduce the probability of breakups. Current strategies for debris minimization include venting excess fuel to reduce the risk of explosion, employing bolt fragment catchers and lanyards to reduce operational debris, and re- or de-boosting spent stages out of high traffic regions. In addition to reducing the sources that generate debris, mitigation also involves the development of strategies to "live-with" background debris environments. Strategies for protecting space assets to live with the debris environment include spacecraft shielding, hardening, and component redundancy. This has lead to recommendations for design improvements through spacecraft component re-alignment and shielding.

Estimates of the future debris environment and the risk posed to Air Force space assets is based on a simple extrapolation of current growth trends. It is significant to note that the deployment of space based weapons systems and the potential for anti-satellite activities in the future could dramatically modify these predictions. Although an active debris program can probably not be justified on the basis of the present debris growth models, the extension of warfare into the space orbit arena and the resulting major paradigm shift in the nature of future armed conflict could significantly change these predictions. For this reason, strategies to increase global presence and control by the deployment of directed energy weapons into earth orbit should be accompanied by a strategy to secure the safety of these assets by managing space debris levels.

Current or Prior Studies or Analyses

Report on USAF Space Debris Phase One Study, Phillips Laboratory, June, 1994

AAS/AIAA Spaceflight Mechanics Meeting, February, 1995

LISK-BROOM Concept Overview, C.R. Phipps, April, 1995

2.12 Extended Range HPM

HPM technology advances will enable HPM weapons to be used at longer ranges in the 10 - 20 year period. For most applications discussed previously under the "10-year" applications, these ranges could be increased by one to two orders of magnitude if component technologies in antennas, power generation, power conditioning, etc. are sufficiently improved during the next decade.

"30 -Year" Applications

2.13 Space Based Laser Weapons (Global Precision Optical Weapon)

Introduction and Background

The idea of space based laser weapons (SBL) was introduced in the mid-1970's as a defense against Soviet ICBMs. The advantage that SBLs offered was the capability of destroying ICBMs in the boost phase, before the boosters could deploy their MIRVs and present overwhelming numbers of targets to midcourse and terminal phase defensive systems. The SBLs could defend the US or its allies against, typically, ten nuclear warheads with each successful engagement - an encouraging leverage.

With the demise of the Soviet Union and the resultant diminished interest in defense against ICBMs and strategic nuclear attack, the focus of the SBL program moved to defense of friendly nations against tactical ballistic missiles. Here again emphasis is placed on boost phase intercept, and the goal is to destroy the boosters before they can deploy defense-saturating numbers of chemical or biological submunitions.

The threat of early post-boost deployment of submunitions is theoretical, since no current TBMs carry such warheads, but it is technically unchallenging to develop them. The threat is a serious one that could appear suddenly and it must be anticipated and countered.

SBLs are one of three approaches to TBM boost phase intercept; airborne laser weapons and air launched hypersonic hit-to-kill missiles are the other two approaches. SBLs offer the advantage of ubiquitous presence - real time global coverage up to some selected maximum latitude. They are also beyond the reach of air defense weapons. Airborne lasers and hypersonic missiles must be deployed to theater before they can be employed, and have range limits that leave some targets out of reach until air control is achieved so that the platform aircraft can roam freely over enemy territory.

The main defect in the current SBL approach to boost phase ATBM lies in the cost per kill or the cost-exchange ratio. A short-to-medium range TBM with chemical or submunition

payloads and crude guidance is cheap compared to, for example, an intercontinental range SS-18s with a sophisticated bus, precision guidance, and 10 thermonuclear armed reentry vehicles, yet the laser energy required and the cost to kill them are comparable. A second defect in the current approach lies in the depth of the deployed magazine. To reduce the deployment costs the proposed constellation has been thinned to marginal utility and the battle stations sized for the minimum required target irradiance. A properly conducted offensive TBM campaign could open a magazine depletion hole in the constellation and have a free fire window with minimal front end losses.

The problems of cost and depletion derive from the technology limitations imposed on the current SBL concept. The laser is chemically fueled; the chemicals react, form the active laser medium, and then are exhausted into space. This approach has the significant advantage of dumping the waste heat overboard, but it results in a magazine that is limited by the fuel deployed with the laser (currently conceptualized as 200 seconds of firing time). When that fuel is depleted the weapon must be either refueled in space or written off and replaced. The proposed battle stations are to be deployed at 1400 km altitude and have a mass of 35 metric tons; either refueling them or replacing them is difficult and very expensive with current technology. Even so, this would be a practical approach if the deployed magazine were sufficient to handle a large number of targets. However, the current limits on wavelength and optics size, together with the long engagement ranges imposed by the small number of battle stations, result in excessive fuel being invested in each kill and the number of engagements in the magazine is small.

Future Technology Directions for SBLs (Developing GPOW)

The SBL concept is intrinsically very attractive, but available technology will only marginally support it. While it remains to be seen whether the high cost of deployment for the proposed approach will prove acceptable, an energy frugal, cost-efficient Global Precision Optical Weapon (GPOW) would have a clearly dominant role in warfare. Better technology will necessarily be needed to realize GPOW's full potential. The required technical directions are:

- Affordable Access to Space. A major reduction in the cost of space launch will be needed. The cost goals originally touted for the shuttle ($100 per pound of payload in low earth orbit) would make GPOW a practical reality. It appears unlikely that our historical approach to space launch, giant multistage rockets, will become low cost, but approaches along the lines of the aerospace plane or possibly gun launch might.
  - A derivative of affordable access to space would be flexible space operations: refueling and maintenance of GPOWs in orbit.
  - If the cost per kill can be lowered sufficiently, targets with low value per item - aircraft and soft surface assets - can be engaged, and the combat leverage of the GPOW can be fully realized.
  - The US no longer maintains singular superiority in either space launch or national economic strength, and it is likely that affordable access to space would see other nations also deploying GPOWs. Our current vision of GPOWs is that only the US has them, and they are employed to dominate terrestrial combat. If, in fact, costs, technology, and combat effectiveness become favorable for

GPOWs, then we must expect competition - similar to what has occurred with every other major advance in weaponry. Space would then become a primary theater of combat, which would be a major paradigm change in warfare.

- Advanced Optics and Laser Technology. Current laser and optics technology does not support energy frugal kill in most SBL scenarios. Much more laser beam energy must be delivered than is needed to kill a booster, and this energy is very expensive ($1 - $2 per joule). To illustrate: killing a Scud type booster requires a delivered fluence of about one kilojoule per cm^2 over a 30 cm diameter area - something less than one megajoule of total energy. However, the currently conceived SBL irradiates a much larger spot at its operating range, and consequently invests much more energy in the kill. The combination of optics size (8 meters), wavelength (2.6 μm), and engagement range (typically 4000 km for the sparse constellation proposed) results in a 3 meter spot diameter - having about 100 times the minimum lethal area and requiring about one hundred megajoules of laser energy to deliver the lethal fluence of one kilojoule per cm^2. With 1600 megajoules of deployed magazine a battle station can engage less than 20 maximum range targets; an energy frugal GPOW design could engage more than 1600 targets.

  - The technical advances that are needed to capture some or all of the benefits of energy frugality are (1) larger optics, (2) shorter wavelength, and (3) improved beam quality. Larger optics is the most difficult goal, both to achieve and to exploit.

    - To put this in perspective with an illustration: a laser with a 1 μm wavelength, operating near diffraction limited through a 20 meter aperture, at an engagement range of 3000 km, will deliver the 30 cm spot size and achieve a minimum energy kill. The laser power required for such a weapon would be modest compared to the eight megawatts of the current SBL conception: a 100 kilowatt laser would deliver lethal fluence (one kilojoule per cm^2) in less than ten seconds - roughly the same irradiation time that the eight megajoule SBL requires at 4000 km. The factor of ten (approximately) reduction in the spot diameter, in this illustration, results from four factors: a reduction in wavelength by a factor of 2.45, an increase in optics diameter by a factor of 2.5, an improvement in beam quality and jitter by a factor of 1.16, and a reduction in the maximum engagement range by a factor of 1.33 (increase in the number of battle stations by about 80%). The wavelength, optics, and beam quality factors have the net effect of reducing the beam spread (1σ) from 360 nanoradians to 50 nanoradians.

    - There are two technical advances of revolutionary magnitude incorporated in this illustration: (a) 20 meter optics, diffraction limited at 1 μm, and (b) 50 nanoradian pointing and tracking. Neither of these will likely be realized through engineering extrapolations of current technology. There is a prospect however that clever extensions of phase conjugation techniques will provide the needed advances. Phase conjugation has been demonstrated (by Russians) to correct meter scale, badly distorted mirrors and optical paths to near diffraction limited performance. This capability, employed in conjunction

with large, very light weight, inflatable mirrors may provide a viable approach to the giant optics problem. Similarly, phase conjugation has been used to provide precision pointing against moving targets, and it may be possible to extend those techniques to long range GPOW engagements.

There are four types of short wavelength lasers that may, with development, qualify for an energy frugal GPOW: (a) chemical HF laser operating in an overtone transition at 1.3 μm, (b) chemical oxygen-iodine laser (COIL) at 1.3 μm, (c) diode pumped neodymium laser at 1.05 μm or ytterbium laser at 1.03 μm, and (d) phased array diode laser at 0.8 μm. The critical qualities of the laser are:

- Beam Quality. The laser must be capable of operating near diffraction limited, either intrinsically or with the aid of adaptive optics or phase conjugation.
- Mass. The laser subsystem, including prime power and cooling, must be light weight, even if major reductions in space launch costs are realized. The laser power required for the energy frugal weapon in the illustration above was only 100 kW, which should result in a very modest mass for the laser generator, whichever approach is selected. The mass of the prime power and the cooling systems will be the distinguishing factors. There are two critical considerations in the prime power and cooling requirements, laser efficiency and operating temperature, and these trend in opposite directions. The two types of diode based lasers have an edge in efficiency, which is advantageous for prime power, but they must be maintained at low (near room) temperature, which results in inefficient or heavy cooling systems.

It should be noted, regarding the electrically driven diode based lasers, that the modest power required by an energy frugal GPOW raises the prospect of closed cycle operation-eliminating the magazine limitations that come with expendable fuels. Since each battle station spends only a small fraction of its time over a combat theater, designs might exploit the inactive time to recycling fuel for fuel cells, using solar energy, and radiatively cooling waste heat reservoirs that employ phase change materials. To illustrate:

- Assume the system is designed to "store" the prime power and cooling capability for 25 one megajoule engagements in the time of one orbit (6000 seconds).
- 4000 seconds per orbit of radiative cooling to space at 273 K, with high α/ε ratio. 0.02 W/cm^2; 0.8 MJ of rejected heat per orbit per square meter of radiator.
- 3000 seconds per orbit of solar energy conversion into fuel for fuel cells, with overall conversion efficiency of 10% (20% solar panels; 50% electrical to chemical conversion). 0.01 W/cm^2; 0.3 MJ of stored prime energy per orbit per square meter of solar panel.
- Waste heat stored in a water-ice slurry during combat. Effective storage capability: 100 J/gm or 100 MJ per metric ton.
- Laser efficiency: 25% from prime power. Need to store 100 MJ of prime energy; store and radiate 75 MJ of waste energy.
  - Need 333 m^2 of solar cells

- Need 94 m^2 of radiator
- Need 0.75 metric ton of water-ice slurry

These numbers are not unreasonably beyond state of the art, and can be viewed as rational goals for the twenty to thirty year time frame.

However, the mass of fuel/oxidizer required for an energy frugal engagement by a burn-and-dump system is not large, and it might be the judgment that there is no need to get sophisticated - just carry enough consumables for a suitably large number of engagements.

Summary

SBLs are the ultimate realization of the military dictum "seize the high ground", and have the potential to revolutionize warfare. However, current technology does not support that potential. Breakthrough advances are needed that greatly reduce the cost of launching payloads to orbit and in optics technology that will permit the use of very large aperture beam directors. Concepts exist that may provide these breakthroughs.

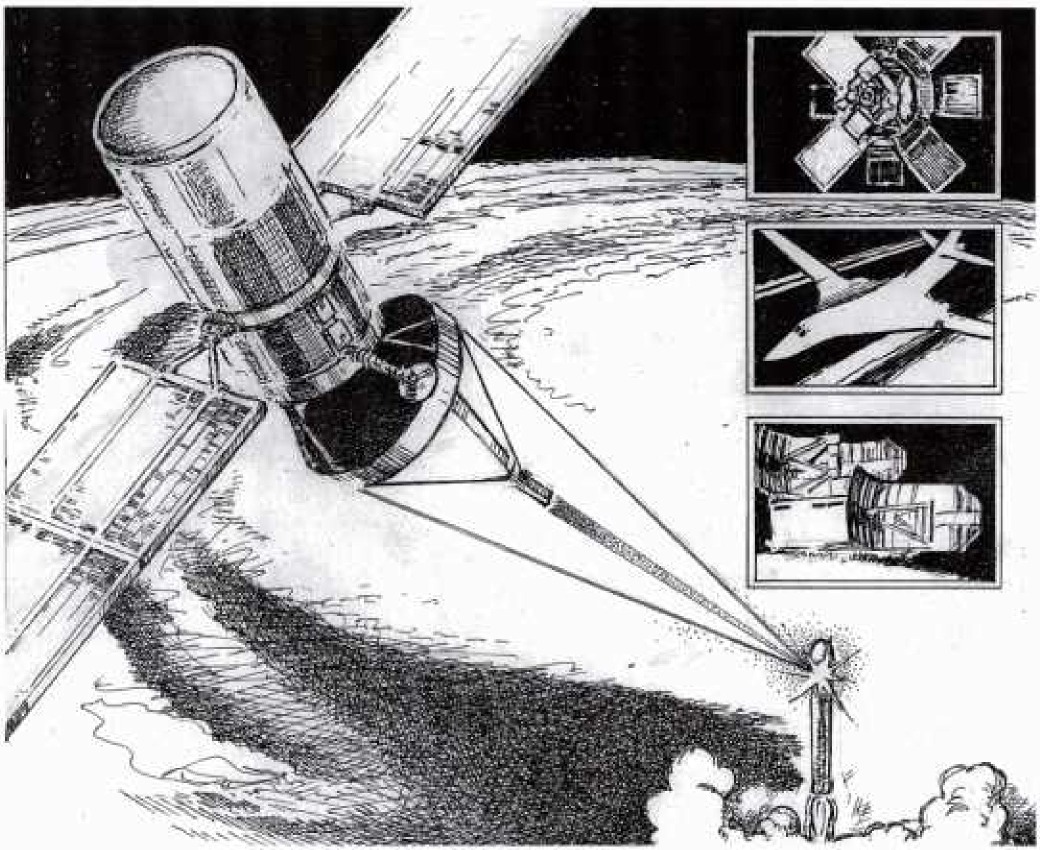

Figure 2. An energy frugal, cost effective Global Precision Optical Weapon would have a dominant role in future warfare.

2.14 FotoFighter

"FotoFighter" is an advanced conceptual fighter aircraft employing a new generation of laser technology now under development in applied research programs. This concept is based upon imbedding an array of diode lasers and sensors in the skin of an aircraft to be used ultimately as a weapon to attack enemy aircraft. Arrays of laser diodes, operated as a coherent phased array, can produce variable power levels and even variable aperture diameters through electronic control of the electrical power supplied to the array. The electronic control of the aperture enables multiple beams, at different power levels, to perform more than one function or handle more than one threat simultaneously. The system has a large off-boresight capability for engagements during high "g" maneuvers. Laser radiation can be used to attack threat aircraft cockpits or other vulnerable subsystems (fuel, aerosurfaces, radar systems, etc.). Laser effects can be used to destroy the target or induce targets to break-off an engagement early. Detector arrays, imbedded in the same or a separate substrate, can provide sensors for a closed-loop optical system. At low powers, the arrays can function as transmitters and receivers for LPI communications. At higher powers, the system can be used to illuminate or track targets and deposit thermal energy. The optical array can be configured to be conformal to aircraft surfaces.

To obtain a 4π sensor field-of-view and a large weapon field of regard, a number of arrays would be distributed over the surface of the aircraft, each array appearing as a "patch" on the surface. The array makes up an aperture for transmitting laser energy and, with imbedded detectors, can also be a sensor for threat detection, acquisition, target tracking, and closed loop beam pointing. Electronic beam steering, over small angles, can be achieved by controlling the phase relationship between adjacent elements to produce a phase front at the aperture which directs the beam at different angles to the surface. Larger angles can be achieved through phase control within each element or through the use of an optical phase shifter within an optical train between the diodes and the aperture. This wavefront control, besides being used to point the beam, can compensate for jitter (tilt) and for higher order phase distortions such as those introduced by atmospheric turbulence.

In the most flexible configuration, each aperture could be electronically controlled to vary aperture size and power output by addressing only the required number of emitters. Multiple beams, independently targeted, could come from a single aperture, and different wavelengths could feasibly be emitted from a single aperture by changing the operating point of the diodes. Experiments have shown wavelength shifts in a diode resulting from optical cavity, thermal, and magnetic field variations. In addition, different diode designs have been operated over a wide range of wavelengths from visible through mid-IR. For further scale-up in power one could combine the outputs of several apertures incoherently, and, although the technique has yet to be demonstrated, one can envision the coherent combining of separate apertures on the aircraft to increase beam intensity at the target.

Some subscale arrays which have been built have employed micro-optics to improve the fill factor at the array surface. The individual diodes making up the aperture have a small emitting area compared to the total area of the array. Improved fill factor within a defined aperture diameter will increase the irradiance in the central lobe of the far-field laser spot, resulting in higher irradiance at the target. The micro-optics, which are produced using micro-electronics processing techniques, are matched to the diodes and behave as lenses over each diode in the array. The diodes themselves have demonstrated very high efficiencies at room temperature

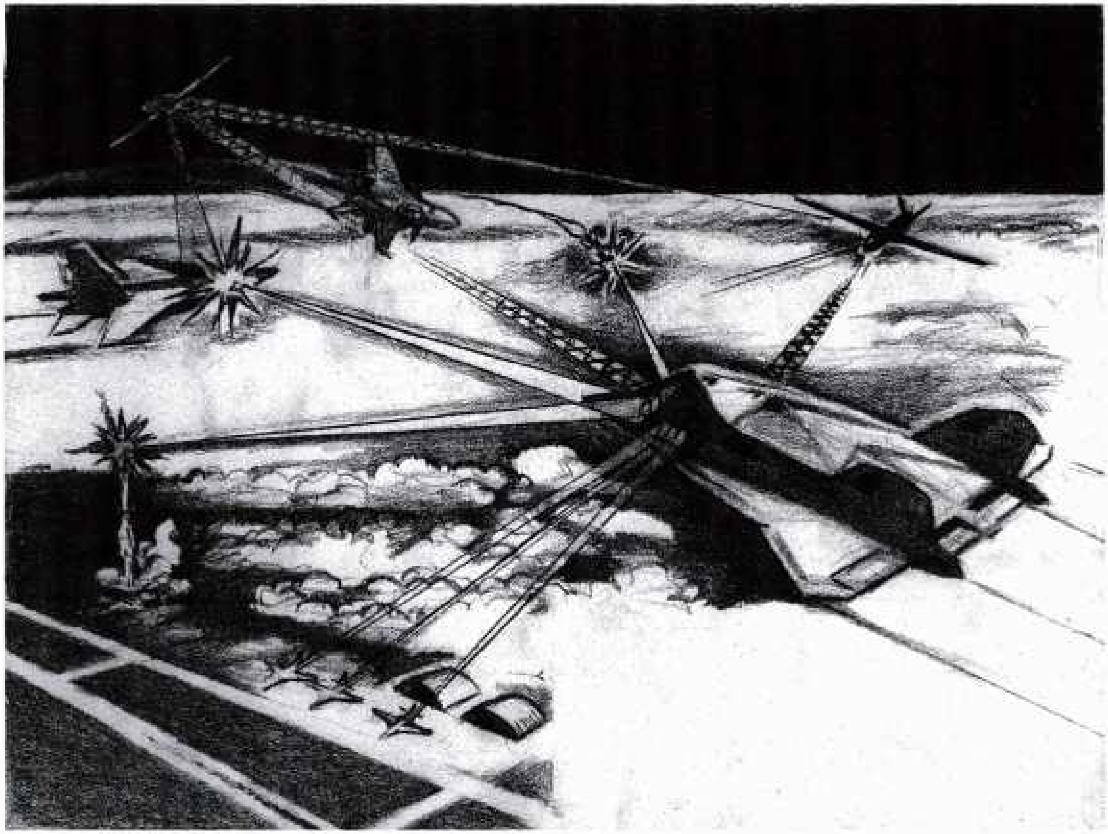

Figure 3. Arrays of phased array laser diodes will enable FotoFighter to perform multiple functions simultaneously.

operation, greater than 50% for a number of different devices. Cooled (to liquid nitrogen temperature) laser diodes have demonstrated efficiencies greater than 90%. In addition, the reliability of diode lasers is unparalleled among all types of lasers. Diodes have been demonstrated for operation for over 50,000 hours in commercial applications. If a few diodes in an array do fail, the effect on the system will be less than a fraction of a per cent in power output for the FotoFighter concept. The combination of high fill factor, high efficiency, high reliability, and graceful degradation create the potential for a very high performance laser system.

Variations on the basic concept would install the diode arrays internally, using optically pumped fiber optic amplifier bundles to bring the laser beams to the surface of the aircraft. This concept replaces the routing of wiring through the aircraft to carry current to the surface-mounted diode arrays with fiber-optic bundles to route the beam through the aircraft to the skin. Because the current demands of the diode arrays can be large, the fiber-optic alternative may be attractive from a weight standpoint.

A diode-based laser concept necessarily involves very large numbers of diodes in the array (10^4 - 10^5 emitters). This implies considerable complexity in the control system for the array if each emitter is to be individually addressable for output or phase control. Concepts for

control of the large arrays have been investigated and, although challenging, appear tractable without losing the attributes of the concept such as graceful degradation.

Two major issues dominate the technology work of the next decade. One is extending the locking range of the diode array - obtaining a coherent output from a large, operationally effective aperture. Some techniques rely on a master-oscillator, power amplifier architecture to extend the array size, while others rely on internal coupling between oscillators (diodes) to increase the coherent array size. The second major issue is the system architecture which allows each element of the array to be addressed for both powering the lasers and for phase control. Thermal control and lightweight conditioned prime power are major engineering issues for subsequent implementation. Integration into the surface of the aircraft represents still another set of engineering challenges, making the operational application of this concept relatively far term.

The inherent flexibility of the FotoFighter concept, which could be applied equally well to other types of aircraft, lies in the many applications of the lasers and sensors to military missions. At low powers, the arrays can provide threat warning, target detection and ID, low-probability-of-intercept wideband communications, visible or non-visible (IR) illuminators, precision designators for other weapons, and a handshake friend or foe function. At higher powers, the lasers can be weapons for self defense, IRCM, or offensive anti-aircraft applications. One can utilize the laser for both its ability to produce optical effects at long ranges or thermal effects at shorter ranges to meet mission objectives.

2.15 Virtual Presence

Global Presence as an element of Air Force doctrine implies presence to deter potential agressors. It encompasses the capability to employ all means of presence: situational awareness, strategic agility, and lethality. Global Presence includes the advantages of physical and virtual means, and includes many concepts, both passive and active. Spacecast 2020 highlighted the high value of Global Presence in all of the alternative futures they examined and stated, "The single most important reason to be in space is to have the Global Presence required to maintain global view".

Virtual Presence is envisioned as a system that is both passive and active, with moderate to high power lasers being employed to transmit interactive presence to distant points of the globe at the speed of light. A network of space optics which are accessible from local and remote ground sites can provide real-time "look-through" capability for in-theater missions. The same optical systems in space can pipe low and high-power laser beams from ground sites around the world to enhance theater operations, and can likewise relay surveillance of the battle-field in real time back to distant observers. A number of potential applications (all conceivably man-in-the-loop) using low to moderate power lasers include: laser scans to develop geocoordinates for precision-guided munitions, man-in-the-loop remote target interrogation, beyond visual range ID, designation of stationary & moving targets for PGMs, battlefield illumination, global atmospherics (LIDAR, etc), identification of friendly forces & air traffic control, standoff detection, anti-terrorism, search and rescue, and advanced situational awareness. The key to this concept of Virtual Presence is the ability to interact in real time with a distant theater of operations through the projection of low and high power laser beams. There are many non-lethal applications of lasers to support theater operations which supplement the surveillance capabilities of the system.

The concept draws from work performed by the Air Force for BMDO (then SDIO) in which a laser beam was projected from the ground to a 24 inch orbiting relay mirror and then back to a target board on the ground to score pointing accuracy over a distance of more than 1000 km. High precision was achieved using a beacon from the target board location for tracking purposes. A more useful concept would use new inertial reference units, now being tested for an advanced acquisition, tracking, and pointing experiment to achieve equally precise open loop pointing, relying on a GPS reference aboard the space-based relay mirror platform.

BMDO studied the architecture for relay mirrors in space, which were to provide the laser beam train to engage and negate ballistic missiles instantaneously, using high power lasers located at a few strategic locations on the ground around the world. The number of ground sites chosen assured access to the mirror network, even when cloud cover produced outages at one or more sites on the ground. The number of mirrors required to obtain good coverage for Virtual Presence will vary from one application to another. An architecture with approximately 15 mirrors at an altitude of about 1000 km would provide near-global coverage with only minor outages. More work is needed to define the network required to guarantee both remote and local (in-theater) access to the mirrors.

Virtual Presence, like GPOW (Section 2.13), requires large space optics for efficient optical linkage around the network and to project a laser beam to a small spot size in the theater. New technology for large space optics is especially attractive to achieve ultra-lightweight and inexpensive space optical systems. Erectable space optics are possible using mylar mirrors or, conceivably, electrostatically formed membrane mirrors. Work in NASA and other laboratories is investigating inflatable optics and electrostatically figured large optical and antenna surfaces. Such large optical elements can be extremely lightweight and potentially economical to produce. They are, however, not sufficiently precise for optical imaging or for projecting a laser to high precision. While adequate for broad area illumination over the battlefield, optically distorted mirrors must be corrected for most other applications.

Key to correcting the distortions is a wavefront compensation element which can cancel the phase distortions introduced at the mirror surface. Techniques for such compensation have been investigated, and have been employed in experimental hardware. Mechanical systems employing deformable mirrors and wavefront sensors have been used for a number of years but more appealing for reasons of cost and simplicity are concepts using micro-electromechanical deformable mirrors for their low potential cost, or non-linear optics which have the potential for combining the sensing and conjugation functions into a single element. The combination of large membrane optics and non-linear optics appear to be enabling for efficient and cost-effective directed energy applications in space.

The pointing of the space-based mirrors can benefit from new high precision inertial reference technology. A stable inertial reference unit has recently been tested in support of the High Altitude Balloon Experiment which demonstrated line-of-sight stability (with a representative input disturbance) to better than 100 nanoradians. This enables open-loop pointing to fractions of a meter, given a good reference for the space platform. This technology can not only assure precise pointing of a laser beam, but is an enabling technology for high precision geo-location.

Another critical element for the concept of Virtual Presence using ground-based lasers and relay mirrors in space is the ability to compensate for atmospheric turbulence on the uplink.

Whether "looking through" the relay system or projecting a laser beam around the world, the atmospheric distortions near the ground telescope must be corrected optically. The Guidestar techniques which are currently being investigated at the Air Force Phillips Laboratory's Starfire Optical Range offer the promise of atmospheric compensation using an artificial beacon or a beacon attached to the relay mirror platforms.

The principal advantage of ground-based lasers and optical telescopes coupled to a network of space-based relay mirrors is that the heavy, expensive laser hardware remains on the ground where access is straightforward. Not only does this facilitate operations and maintenance, but the laser fuel can be readily replenished, and lasers can be interchanged as may be desirable for different applications.

The concept of Global Presence, which is all too frequently limited to global surveillance, is greatly enhanced by introducing directed energy as a means to interact with the theater in real time for a wide variety of applications leading to greater situational awareness and the ability to influence events in a distant theater prior to the movement of personnel or materiel.

3.0 Technology

3.1 Diode Pumped Solid State Lasers

Diode pumped solid state lasers (DPSSL) have made remarkable technical advances over the past five years, and there is reason to believe that significantly greater advances are yet to come. The critical question is whether those advances will be sufficient to support the development of practical laser weapons - weapons that are both adequately lethal against flying targets and compact enough for air or space deployment. The prospects for such advances are hopeful.

The major areas where advances are needed, and possible, are:

- Cost of Diodes. Currently diodes cost about \$10 - \$20 per peak watt, and four to ten times that per average watt. Diode output to laser output is typically about 20 - 30% for neodynium, ytterbium, or thulium DPSSLS. So, diode costs add up to several hundred to a thousand dollars per average laser watt. This is marginally acceptable for low power lasers, but obviously is too high for lasers in the 10 kW or higher power range.

  There are two primary processes to reduce substantially the cost of such devices. One is large scale production. Current production and assembly techniques would support a ten-fold reduction in cost if they were implemented at large production scale. This would open the door for 100 kW class lasers. Megawatt class lasers will need another ten-fold cost reduction, and this will require new fabrication and assembly techniques, as well as a market supporting large scale production. The market creation for large scale production is a very important element in that high volume production costs cannot come down if a major market is not created for such product. The one attempt in the US for large volume production failed for laser diode pump primarily because it did not offer the product at prices that would have created a new and substantial market for the product. To create such a large volume market would have required to sell the product at a "loss leader price." After the substantial investment of capital to pay for the costs of automated production, industry involved could not take the additional costs of a "loss leader."

  The second approach is through enhanced performance of diode bars. Currently, the AlGaAs diodes are capable of producing the order of 25 watts of average optical power per centimeter of diode bar. The production cost is in the diode bar. If the power level of such diode bar could be substantially increased, then the effective cost per watt of pump power could come down, even if the diode bar price remains the same. In effect, one would need fewer diode bars to pump a given laser. Diode facet damage currently limits the diode power output, yet theoretically, it could be raised to a power of the order of 250 watt/diode-em level, a 10-fold increase, with certain diode technology development. New fabrication techniques (planar surface-emitting arrays, in contrast to the current stacked linear edge-emitting arrays) are in development, and if successful, should lead to significant cost reduction. Whether the market will become large enough to drive the costs into the 10 cents per peak watt range is uncertain. Military demand alone will probably not be sufficient for this, and thus far commercial demand for high

power systems is quite limited. However, the cost-market bootstrapping process may trigger off a combined military-industrial fabrication customer set. It should be noted that ytterbium DPSSLs (wavelength 1.03 gm) have a diode-to-laser efficiency about two times higher than neodynium DPSSLS, because of their longer excited state lifetime. While neodynium has received most of the development attention thus far, it may be that ytterbium will be the better approach to high-power laser weapons.

- Efficiency. Currently diode efficiency is about 45-50%, and diode-laser efficiency is about 20-30% for neodynium, for a net efficiency of 9-15%. Efficiency impacts the diode array cost, the size of the prime power supply, and the size of the cooling system, and overall the size and cost of the system. In the next two to three decades routine engineering advances, driven as much by the commercial as the military market, should improve these efficiencies to 60% for the diodes, and 30% for the diode-laser transfer-roughly doubling the net efficiency of DPSSLs from the current value. Switching to ytterbium would provide another factor of two improvement.
- Thermal Management. Diodes do not tolerate high temperature. They operate best below 350 K - 400 K, the further below the better. Additionally, diodes shift wavelength with temperature and typically must be operated over a narrow temperature tolerance range. It is unlikely that these basic facts will change very much in the foreseeable future. Removing waste heat at low temperature and with small gradients is generally an inefficient process, inefficient in heat transfer out of the material, in storage of waste heat, and in transfer to whatever final heat sink is employed (e.g. the atmosphere or space). Making the best of this difficult problem is likely to involve various incremental engineering improvements, rather than a radical breakthrough. Additionally, whatever interest the commercial sector has in high power systems will be in fixed installations where open-flow water-based cooling can be employed. So advances in this area will likely come from the military, if at all.

One radical development has occurred, however: microchannel cooling has greatly improved the heat transfer process in diode arrays (1 kW/cm^2 at room temperature with a 20°C temperature difference between the cooling water and the diodes).

A second recent innovation of some potential importance in scaling DPSSLs to high power is the development of InGaAs diode arrays operating in the 900-950 nm range together with the development of ytterbium (Yb) doped laser crystals. The Yb ion generates roughly one third as much waste heat per output photon as neodynium (Nd), which will greatly relieve the waste heat problem. This, in addition to the factor of two improvement in pumping efficiency the Yb offers, will be a critical factor in laser weapon design.

Thermal management of the laser material can be approached in two ways: (1) arrange the material in thin slabs or in fibers, so that the thermal diffusion path is short, or (2) exploit the sporadic nature of weapons employment in combat and design the laser to have sufficient material to store the waste heat over a typical firing cycle. In this second approach (heat capacity operation) the thermal capacity of the laser acts as a "magazine" that specifies the total energy output of the weapon; the "magazine" is reloaded by cooling the laser to start the cycle over.

Heat capacity operation applies only to the solid state laser and not to the diode pumping array, which has negligible heat capacity and must be cooled during operation.

Whichever approach is employed, efficient diode pumping is an important element in the thermal management, since it deposits the minimum amount of waste heat in the laser for a given laser output energy.

Heat capacity operation has been much analyzed, but not yet developed. It works best with crystal host lasers, which have a higher heat conductivity and resistance to damage by thermal shock than do glass hosts. These advantages permit crystal hosts to be more rapidly cooled between operating cycles. It should be possible to engineer diode pumped crystal host lasers to yield between 500 and 1000 Joules per cm^3 of host material during a firing cycle (about a tenth as much for glass host lasers). Thus, between one and two liters of host material, weighing 6 to 15 kg, would be required for each megajoule of magazine capacity. Efficiently conducted engagements (minimum damage area to achieve lethality) against small tactical missiles would require several tens of kilojoules, while boost phase missiles would require about a megajoule.

True continuous operation at weapon power levels is probably not practical with today's laser designs and cooling technology. Those designs are based on thin slabs of laser material that are face cooled by flowing gas, and the heat transfer to gas is simply too slow to extract high power per unit volume. It may be possible to achieve continuous operation with designs based on diode pumped glass host fibers with liquid cooling. Suitably large arrays of such fibers could yield weapon level power. The primary challenge in this approach is controlling the phase front of the output to get diffraction limited performance. This will require invention; possibly phase conjugation can be employed for this task.

Size and Weight

The size and weight of high power DPSSLs are primarily determined by the thermal management system employed. The laser amplifier and the diode pumping arrays are small, and prime power generators have been engineered for compactness. Heat capacity operation yields the most compact designs, since it cools only the diode arrays in real time. The narrow temperature tolerances of diode arrays argue for the use of a phase change heat sink in the diode cooling system. Many options exist for a diode heat sink, but a water-ice slurry is illustrative. Ice will absorb 330 joules/gm in melting, and a water-ice slurry could probably be operated at a net of 150 joules/gm capacity. A laser with 60% efficient diodes and 30% optical-optical efficiency would generate 2.2 MJ of waste diode heat for each MJ of laser output energy, and thus would require 14.8 kg of water-ice slurry for each MJ of laser output. This is not at all excessive, by itself, and the major size/weight penalty would be found in the plumbing and pumping hardware. If the same water-ice slurry were employed to cool the laser between operating cycles the laser would require an additional 15. 5 kg of slurry for each MJ of output. Thus, a laser sized for 10 MJ in an operating cycle, and 10 operating cycles in a mission, with no external heat exchange throughout, would require 10 to 20 liters of laser material, weighing 60 to 150 kg, and about 3000 kg of water-ice slurry. If the laser were externally cooled between operating cycles the slurry mass would be reduced to about 1500 kg. If the laser and the slurry were both cooled between cycles the mass would come down to 150 kg, and the number of engagements stored would be defined by the prime power supply.

It should be noted that DPSSLs do not have an advantage over combustion lasers in terms of the mass of "consumable" fluids. DPSSLs could get about 30 to 60 output joules per gram of liquid. Combustion lasers are several to ten times better than that. DPSSLs, however, can work with the fluids entirely in the liquid phase, which conduces to compactness, while combustion lasers must be designed to handle a large volume flow of low density gas. Additionally, "reloading the magazine" for a DPSSL is a matter of cooling to the environment, as contrasted with visiting a fuel dump. The distinctions and relative merits of the two approaches are to be found in the engineering details of the plumbing and the overall operational processes as well as in the "consumable" mass.

Beam Quality

Solid state lasers do not easily yield high quality beams, particularly at high power. Phase conjugation has been exploited at low to medium power in several different configurations to compensate for the optical path distortions typically occurring in dense solids and near diffraction limited operation is routinely achieved. Extending these techniques to high power appears to be possible, if not trivial, and it seems clear that whatever configuration of DPSSL may be employed in the laser weapons of the future it must be a configuration that is compatible with one or another version of phase conjugation.

Conclusion

There appears to be a straightforward engineering path to the development of weapon scale DPSSLs. Such weapons might be sufficiently compact to open the door to tactical air-borne applications, and provide an alternative approach to space based lasers that may remedy some of the limitations afflicting the current approach. The most critical aspects of technology advance needed are low cost diode array fabrication techniques and compact thermal management designs.

3.2 High Power Semiconductor Lasers

Semiconductor lasers have a number of advantages over conventional laser systems that make them ideal for many military applications:

- They are highly efficient (> 60% wall plug has been demonstrated compared to < 10% for conventional lasers)
- They are scalable to higher powers (there are now kW incoherent arrays commercially available)
- They are microelectronics based, which means they can be mass produced, resulting in low cost,
- Only low voltages are required, therefore, they can be battery operated
- They are compact
- Because they are solid state (no moving mechanical parts, i.e. external mirrors etc.) they are reliable (> 50K hours have been demonstrated)

- They are also wavelength agile (the wavelength can be easily changed by changing the band gap of the material)

If the optical phase of the light from each diode in an extended array can be controlled, an optical phased array can be constructed, which is scalable to high power, and can be pointed and focused electronically with high precision.

Future applications of the phased array of diode lasers are numerous. The phased array could be used for full 4π beam steering with single or multiple beams of different wavelengths. Output could be varied from very low to very high power. No additional power sources would be required other than existing aircraft power. No chemicals or hazardous reactants would be needed. An aircraft with an array of semiconductor lasers embedded in the skin could use the light to damage optical sensors or other vulnerable subsystems (fuel, aerosurfaces, radar systems, etc.) or to thermally destroy targets or induce targets to breakoff an engagement early. The same device could be used for illuminating and tracking targets. Sensors could be integrated on the same substrate as the laser array for closed loop operation. At lower powers, the device could be used for secure air-to-air, or ground-to-air communications.

The "FotoFighter" concept is based upon imbedded arrays of diode lasers and sensors in the skin of an aircraft. The lasers are to be used for multiple functions: illumination, communication, designation for precision guided weapons, and directly as a thermal weapon. The sensors are also multi-functional, providing for target acquisition, target imaging, and laser beam control system. The current research effort within the Air Force is to develop scalable technology for high power, coherent laser sources using semiconductor lasers and laser arrays.

The High Power Semiconductor Laser Technology (HPSLT) program at Phillips Laboratory is concentrating its efforts in three areas: single devices, alternate wavelengths, and coherent arrays. The single device work is developing high-power single devices with good beam quality that can be integrated into the scaling architectures developed under the coherent array effort. The alternate wavelength work is investigating material systems that will produce wavelengths ranging from red to 2 -5 microns. These devices will also be integrated into the scalable arrays. The coherent array effort is investigating array scaling technologies including master oscillator power amplifier (MOPA) configurations, coupled oscillator configurations, and external cavities.

When the HPSLT program started in 1984, good beam quality semiconductor lasers were limited to less than 50 mW output power at a limited range of wavelengths. Since that time, the technology has experienced a tremendous growth in every area. A single laser can now produce over 5 watts of power with good beam quality. The early devices, typical Fabry-Perot semiconductor lasers, required very narrow emitting regions (3 - 5 μm) to obtain good beam quality. If the emitting region is broadened to obtain higher powers, nonlinearities in the material result in self focussing which, in turn, result in filamentation and poor output beam quality. New high-power structures are broad area devices designed to suppress filamentation. Four single device configurations appear to be promising. First is the off-axis amplifier or resonator. This type of device reduces the filamentation by distributing the light more uniformly in the gain region. Six hundred (600) micron stripe widths have been demonstrated with good beam quality. Over 21 watts of output power have been obtained from an amplifier externally injected by a Ti:Sapphire laser. Next is the on-the-chip unstable resonator. A curved mirror is etched on one facet of the

laser to form an unstable resonator. This reduces the filamentation and allows the stripe widths to increase from 5 microns to 400 microns. The unstable resonator is now producing 3 W pulsed power from each facet (6W total). The third approach is the tapered amplifier/resonator. The contact to the amplifier is tapered, allowing the light to diverge as it travels,across the gain region, suppressing the tendency to filament. This idea was tried several years ago with very little success. With the tremendous improvement in material quality, this configuration is now producing high output powers with good beam quality. The tapered (or flared or funnel) amplifier is one of the most promising new single device structures being developed.

SDL, Inc. has a commercial product based on this device which emits 750 mW of single mode light, however more than 7 watts of power has been achieved from this type of device. Finally, the newest single device structure is the chirped grating, unstable resonator being developed by Hughes Danbury Optical Systems. It works on the same principle as the above structures, allowing high powers with good beam quality. Over 9 watts of CW power has been demonstrated.

Some of the technical challenges are to understand the "alpha" parameter in the material systems, which has a direct relationship to the filamentation, and to be able to obtain very high damage threshold anti-reflection coatings for these new high power devices. Experiments have shown that semiconductor lasers are extremely sensitive to optical feedback and at these high power levels, good coatings will be crucial. Another challenge will be to modulate the devices at sufficient rates for communication applications. The near term goal of the program is to obtain 10 watts from a single laser by the end of the calendar year.

The majority of the work done on the single device development has been in the mature material systems of AlGaAs and InGaAs. These materials lase between 800 and 1000 nm. Commercial devices today are limited in range from about 690 nm to 1500 nm. A great deal of interest has been shown for lasers at other wavelengths for IRCM, sensing, and other applications. There have been significant advances in new material systems to obtain longer wavelength lasers. Sb-based systems have been used to demonstrate room temperature operation at 2000 nm (1.3 W) and cooled operation up to 4000 nm (100 mW). On the lower end, 0.5 watts of 630 nm light has been obtained - the highest power levels achieved to date. The challenge is to develop high quality material for room temperature operation. Sb-based systems can theoretically go out to 5000 nm. The goal of the program is to go to 5000 nm and incorporate the broad area single device structures to obtain good beam quality.

Significant advances have also been made in phasing arrays of semiconductor lasers. Array coupling schemes with over 1000 lasers phase-aligned in a two dimensional array have been demonstrated, using both the MOPA and external cavity approaches. Total system efficiencies range from a few percent to 15%. In developing the phased arrays, supporting technology such as distribution networks, phase shifters, heat sinks, and other key integrated optics technology have evolved. In the MOPA systems, beam steering is straight forward by applying a current to each amplifier to adjust the phase, however it is limited by the spacing of the emitters. An external beam steering system has been investigated by the Air Force that will increase the beam steering angles, but is still limited. Key challenges are to incorporate the new high power single devices and material systems into the proven array architectures, increase the beam steering capabilities, and improve system efficiencies. Near term goals are 100 watts from a phased array at the end of FY 96 and 200 watts at the end of FY 97.

The Air Force research programs and concepts have stimulated important advances in the commercial laser R&D world. One laser system concept which has growth potential to weapons, brings together the technologies of very high power fiber optic amplifiers and the coherent combination of many fundamental mode beams. Individual fiber laser powers in excess of 10 watts have been demonstrated. Operation is currently possible in a variety of wavelength bands in the near-IR, depending on the rare earth dopant used in the fiber core. High power semiconductor laser pump devices and arrays under development in the ongoing HPSLT programs will enable single fiber laser powers approaching the fluence limits of the fibers themselves - in excess of 100 watts, fundamental mode, per fiber. This is accomplished at very high overall efficiencies.

Scaling this fiber laser technology to weapon-class powers requires that the output of many fibers be coherently combined. Technology evolved from that developed in the HPSLT programs for combining 1000 semiconductor laser outputs coherently is applied. All fiber optic amplifiers are slaved to a common master oscillator through a signal distribution network, and provision is made to individually control the output phase of each fiber beam with respect to the master oscillator signal. Advances in control techniques allow he individual phase control of systems with more than 10,000 beams, resulting in a weapon-class solid state laser system.

There are several desirable characteristics of this multi-beam, fiber optic laser concept. First, it is scalable literally from tens of watts to megawatts, using the same basic building blocks. Second, the aperture of the laser is formed remotely from the laser and optical amplifier hardware using fiber optics as the beam transmission means to the aperture. The aperture can be formed at the skin of the aircraft, in a Fotofighter application, and power from a single bank of optical fiber amplifiers can be optically switched from one aperture to another around the Fotofighter. Third, dynamic beam forming, steering, focus and atmospheric correction can be implemented directly in the beam combining phase control medium. Fourth, the fiber optic amplifiers typically have a gain bandwidth of ~ 30 nanometers, and within that band operate as linear amplifiers. This means tha some degree of dynamic wavelength tuning can be employed to defeat narrowband filters or to avoid atmospheric absorption peaks. It also means that multiple master oscillator wavelengths can be amplified sumultaneously.

In the nearer term, diode laser arrays could be used to pump solid-state or fiber lasers to achieve high power levels at mid-IR wavelengths (see section 4.1). Existing programs have demonstrated short range secure communications, scalability potential, wavelength agility and many of the supporting technologies. Longer range communications, chemical sensing, access denial, and jamming demonstrations are planned in the next five years. Long term plans include continued development of the technology to achieve the final goal of a lightweight, aerodynamically efficient, versatile system for applications such as weapon self-defense, IRCM, anti-craft, antiground targets, LPI wideband communications, IFF, illuminator-designator, etc. This program has been very successful in advancing the state-of-the-art in diode lasers in the United States and will continue to do so well into the 21st century.

3.3 Chemical Oxygen Iodine Lasers

The Chemical Oxygen Iodine Laser (COIL) has been under development at Phillips Laboratory since the early 70s. Since the first scaleable supersonic COIL was demonstrated in 1984, the emphasis has been on demonstrating the ability to scale the COIL for ground based

applications as part of the Ground Based Laser Technology program. In the past several years the emphasis has changed to the ability to provide a lighter weight, more efficient COIL. This work is ongoing is support of both the Airborne Laser Program and the Ground Based Laser Technology program. In addition, a number of advanced applications of "COIL" or derivative laser concepts are being explored.

The COIL laser has a distinct advantage over other industrial lasers in that it couples with and is transmitted by optical fibers very efficiently. This has the potential to decouple the "laser" area from the "workbench" area in industrial applications. One specific application which is being explored is the Decontamination and Decommissioning (D&D) of obsolete DoD, DoE, and civilian nuclear reactors and nuclear material processing facilities. In this application it is very desirable not to have to operate the laser itself in the contaminated environment. This application centers around the capability for high power (10 to 30 kW) delivery of a COIL beam through a single fiber optic cable to a remotely-operated tele-robotic manipulator working in a hazardous environment (radiation or chemical contamination). The laser beam would be used to cut thick sections of contaminated metal and/or concrete into manageable pieces for cost-effective storage or disposal. The high-power beam could also be used for stripping contaminated surfaces for the purpose of minimizing the volume of high-level waste that has to be disposed of. Potential near term applications include the dismantlement of DoE reactors in preparation for component disposal, D&D of DoE nuclear weapons production facilities, and D&D of shut down commercial nuclear power plants. The development of this technology can lead to new, innovative, and cost effective laser materials processing methodology which can be transitioned to industry. Key technologies which require further demonstration include metal surface stripping and high power fiber optics delivery.

The Airborne Laser designs require pulsed illuminator beams near (but not at) the wavelength of the weapon laser (1.315 microns). Currently several diode pumped solid state lasers in the 1 to 1.3 micron range at powers of several kW and rep rates of thousands of Hz are planned. The first scaling step toward this capability (ATLAS) is being developed by TRW for Phillips Laboratory. This laser will be delivered in the fall of 95. An alternative is to pulse a COIL laser using a magnetic field around the cavity. Over the past several years the ability to pulse the COIL at high efficiency and rep rate has been demonstrated using this technique. The high peak intensities early in each pulse should lead to reasonable efficiencies in frequency conversion. Efficient frequency doubling using a nonlinear optics crystal has been demonstrated. Raman shifting to wavelengths in the vicinity of 1.5 microns has been examined analytically and appears practical. Raman conversion is routine on solid state and other laser systems. It remains to be demonstrated on COIL but is not anticipated to be difficult. If the ongoing solid state laser scaling efforts stumble or if the illuminator power requirements grow, this COIL illumination concept may become attractive.

The COIL laser is different from other chemical lasers in that the thermal load is absorbed in the liquid reactant (BHP - a mixture of Hydrogen Peroxide and Potassium Hydroxide). This has advantages in terms of the operation of COIL devices such as low temperature operation, low mach number operation, ease of material selection and manufacturing. The main disadvantage is that the liquid reactant is heavy. Several alternatives are being explored which replace the single delta oxygen which currently acts as the energy transfer species in COIL lasers with isoelectronic molecules such as NCl and NF. In the NCl version, a stream of Helium and atomic

Fluorine from a combustor is injected with a mixture of Helium, Iodine, and Deuterium Chloride. The Deuterium Chloride reacts with some of the Fluorine to produce Deuterium Fluoride and atomic Chlorine. The molecular Iodine is dissociated by Fluorine atoms to atomic Iodine. Into this flow, Deuterium Azide is injected. This reacts with the Fluorine to produce DF and N_3. The N_3 then reacts with the atomic Chlorine to produce single delta NCI which pumps the Iodine atoms in an analogous manner to the oxygen single delta in the COIL laser. The key reactions have been demonstrated using premixed gases at universities. The critical rate constants have been measured and there are no identified show stoppers. Phillips Lab is currently building a small flowing system as the first step on the path to determine the feasibility of this laser. In theory, this laser could be several times more weight efficient than COIL since it is based entirely on gas phase reactions. This technology is about where COIL was in the late seventies. A variant of this idea is to use single delta NF as the energy transfer species. In this laser type, a stream of Deuterium and Fluorine atoms from a combustor similar to that used in HF lasers is injected with a stream of either NF_3 or N_2F_4 creating the single delta NF. Molecular Iodine is injected in a supersonic nozzle, dissociated, pumped, and lased in a manner analogous to current COIL lasers. This process has not been demonstrated but it is a combination of existing HF and COIL technology and is supported by the measured reaction rates.

3.4 Laser Frequency Agility

Introduction

Optical sources operate at very high frequencies compared to RF sources, 10^{14}-10^{15} Hz versus 10^{9}-10^{11} Hz. This allows an optical source to have a large degree of frequency agility compared to what is achieved in the RF region. For example, $\nu \sim 3 \times 10^{14}$ Hz at a one micron wavelength, so a 1 GHz bandwidth or frequency chirp is only 3×10^{-6} in ratio of bandwidth to frequency ($\Delta\nu/\nu$). The linewidth of typical solid state lasers ,such as Neodynium: YAG, is $\sim 7 \times 10^{-4}$, so a laser will have high gain over many 100's of GHz. This means that:

- Broadband or frequency agile communications may still be very narrowband optically.
- The optical analog of very broadband RF swept sources may still be in the medium bandwidth range optically. In the optical domain 0-40 GHz $LiNbO_3$ traveling wave modulators have been used to superimpose broadband RF signals on an optical frequency carrier. (This approach is being actively pursued by all three Services because of the potential for very light weight phased array receivers and transmitters using optical fibers to distribute phase reference signals.)
- True broadband optical sources, with a bandwidth of 10% or more of the wavelength are also possible. They can have a frequency sweep well beyond normal RF capabilities and are of two principle kinds: very broadband atomic, vibronic or ionic laser systems, or nonlinear optical frequency converters to shift laser wavelength to one or more different wavelengths.

Both types of approach have strengths and weaknesses which are intrinsic to the mechanism being used (i.e. no free lunch).

Status in General

There have been a number of demonstrations of generic capabilities but usually these have been much more illustrative than specific in simultaneously demonstrating all of the performance measures that a real system would need;

- The range of frequency tuning is the usual measure reported but frequency stability is not usually cited.
- Tunable ranges may not coincide with atmospheric windows.
- Temperature effects most likely source of performance drifts for either type of tunable source but they may have different realizations in the two types of sources:
  - Tunable laser sources are subject to heating due to waste heat in the laser cycle, just like any laser. Generally it is worse for a tunable laser since broad gain linewidth implies short upper level lifetime (from the definition of the Einstein 'A' and 'B' coefficients) and this implies extra heat required to maintain net gain.
  - Heating in a non-linear converter crystal affects the indices of refraction (through $dn_{o,e}/dT$) and hence the wavelength(s) which are generated in a "phase-matched" process, as well as the ordinary thermal effects of lensing and birefringence (which may be very complicated in these crystals). The source of the heating is not usually intrinsic to the process but an artifact caused by impurities or defect centers in the crystal.

State-of the Art (mid-1995)

- Tunable $TiAl_2O_3$. LLNL has demonstrated ~ 50 watts from a cryogenic device pumped by ~100 watts of Argon Ion lasers.(Cooling to 77 K increases the thermal diffusivity and also decreases dn/dT; the net improvement over room temperature operation is a factor of 200 improvement in thermal handling.
- Frequency converted Neodymium: YAG. Laserscope (1993) reported 100 watts at 532 nm from an internally frequency doubled lamp pumped laser. The DAPKL laser at TRW (1995) produced more than 250 watts of 532 nm output at 100 Hz repetition rate from a KTP crystal.
- Infrared (3-5 micron). Optical Parametric Oscillator outputs are in range of 3-4 watts of total IR output (1995). The low outputs relative to frequency doubling are because of deficiencies with present OPO materials. AgGaSe has low absorption, but also a very low thermal diffusivity (0.012 watts/cm-K). ZGP has high diffusivity (0.60 watts/cm-K), but also has a very high 2-3 micron absorption (>20% /cm).

Future State of the Art

- New tunable atomic/vibronic laser possible in near UV through mid-IR; power levels of 1-10 watts for fieldable devices; higher for laboratory. These materials already have found many commercial uses which encourages commercial materials improvements.

- Better nonlinear converter material probable either by improved growth techniques for known crystals or fabrication of new implanted or fusion bonded structures. 10 watts mid-IR seems probable in 1-3 years with cooled crystals; 100 watt powers are conceptually possible if absorption can be reduced enough as it is not intrinsic to the conversion process.

3.5 Adaptive Correction and Pointing Using Brillouin Enhanced Four Wave Mixing

The future success of laser-based directed energy weapons (DEW) critically depends on the scaling of laser irradiance delivered to the target. Even with optimistic projections of new technology which should greatly reduce the size and weight requirements of laser weapon systems, a key aspect of increasing this delivered irradiance will be the decrease in beam divergence. This can be achieved by decreased output wavelength, increased laser beam quality, and increased beam director diameter. The result should be an energy frugal precision weapon with improved efficiency, effectiveness, and magazine depth. To enable these advances, however, active adaptive wavefront correction will be required to generate the required beam quality in the directed laser beam to target. Aberrations in the high power laser gain medium, errors in laser optical surfaces, atmospheric and flight turbulence distortions, and imperfections in large, light weight beam director mirrors will have to be compensated down to <1/10 wave at a wavelength of 1 μm to achieve a desired < 2 x diffraction-limited beam divergence. A second and related issue is that with this reduced beam divergence, pointing accuracy requirements for reliable target engagement are increased. A possible method of achieving the required small beam spot size which is accurately positioned on the target is the use of adaptive optical systems. Wavefront sensors which diagnose light returned from the target generate phase error information which is then fed back to deformable or multi-segment adjustable mirrors or optical light valves to cancel these errors. This is a demonstrated technology which has been successfully used in Air Force directed programs to correct atmospheric distortions in a ground-based 1.5 m aperture.

An alternative to conventional adaptive optical techniques is passive correction and pointing using degenerate four wave mixing. This concept uses nonlinear phase conjugation in such a way as to automatically direct all of the energy available in a laser amplifier chain onto a target illuminated by an auxiliary laser. The initial motivation for research in this area was the prospect of improving the target illumination uniformity and decreasing design complexity in laser inertial confinement fusion (ICF) laser systems. The general concept of adaptive pointing is easily understood. A weak illuminator floods the general area of the target and a small fraction of the radiation scattered from the target is collected by an optical system and directed into a laser amplifier. This received beam may be significantly aberrated and may suffer additional distortions through the amplifier chain. The beam passes through the amplifier, increasing in irradiance, and then is directed into a phase conjugate mirror (PCM). The Stokes return from this mirror propagates back through the amplifier where it now efficiently extracts the stored energy. Given the wavefront reversed properties of the Stokes beam, all of the aberrations present in the first-pass beam are compensated and it returns precisely to its place of origin, in this case, the target. The weak illuminator beam can therefore control the pointing direction of the powerful conjugate beam, insuring intense target illumination.

Although this basic idea was first suggested by US researchers (V. Wang, 1977), it has received the most attention and development by researchers in the former Soviet Union by a significant margin. In the past 10 years, considerable progress has been made in increasing the sensitivity of the PCM. The most significant development in this regard is the use of Brillouin-enhanced four wave mixing which provides threshold-free operation with very high achievable gains. In this scheme, a stimulated Brillouin scattering (SBS) cell contains a reference beam (1-10 J typical) and its counter-propagating Stokes phase conjugate beam in a near collimated geometry. The beam irradiance is adjusted such that the SBS nonlinear gain is held below 20 nepers to prevent self-oscillation from noise. The weak target return signal is directed into the cell where it is amplified and wavefront reserved by a four wave mixing interaction. Polarizing beamsplitters provide the required isolation between the pump and signal beams while quarter waveplates around the SBS cell establish the required interfering polarizations in the nonlinear medium.

An important energy scaling scheme provided by this technique is the phase locking of multiple amplifier apertures. By using a single nonlinear reference cell for multiple laser amplifier channels, each of the output beams are automatically aimed to the same target. Furthermore, temporal phase locking between each aperture results in coherent beam combination such that the divergence of the total set of beams has the narrow divergence achievable from the dimensions of the whole array rather than the larger divergence of a single aperture. For moving targets at large distances, the optical time of flight between the laser and target must be considered. The nonlinear adaptive pointing technique will very accurately direct the laser to the exact point the target was located at the time of illumination by the designator laser, possibly missing it because target motion during the round-trip optical transit period. This can be remedied in a straightforward fashion by introducing a fixed frequency shift on the nonlinear amplifier reference beam input. The resulting change in the diffraction angle off of the nonlinear holographic grating can then introduce the required programmed point-ahead to the target.

The work of Soviet researchers (Andreyev, Matveyev, Pasmanik) has provided theoretical predictions and experimental verifications of the lowest power of a weak signal wave at which it is still possible to separate the conjugate signal from the noise background in either the nonlinear or the laser amplifier. A very simple understanding results in the requirement that in order to approach the quantum limit, the laser amplifier must have a small signal gain that will amplify a signal photon to a level that exceeds the single mode thermal noise in the SBS amplifier. This is given by $kT/h\Omega$ where Ω is the Stokes frequency shift. For typical SBS media, this places the laser amplifier gain requirement between 60 and 2000 which is easily achievable. Lower limiting sensitivities of 10^{-17}-10^{-18} J have been demonstrated. Recent conceptual development by A. Betin has refined the technique to potentially illuminate only a smaller portion of an entire target by selective spatial filtering in the Fourier plane of the SBS interaction. G. Pasmanik has recently proposed a scheme in which short pulse designator pulses can be used to wavefront control long duration high power pulses using forward SBS pulse stretching.

Wavefront correction by nondegenerate four wave mixing should prove useful in a number of directed energy missions such as laser illuminators and weapons as well as specialized applications such as orbital debris removal. This technology can enable energy frugal laser weapons by providing very narrow divergence, automatically pointed laser energy to a target

using large, lightweight beam director mirrors with less than the required optical figure accuracy. Nonlinear wavefront correction techniques are often perceived as being complicated and sufficiently exotic to exclude them from real fielded applications of laser systems. However, as SBS phase conjugation enters the mainstream as the key supporting technology for high average power solid state laser systems for both DoD and industrial applications, this perception will change. The large amount of sophisticated hardware, electronics, and computational power required for modern adaptive optical beam control using segmented or deformable mirrors certainly warrants further investigation and testing of nonlinear adaptive pointing for directed energy applications.

3.6 Stimulated Thermal Scattering Nonlinear Wavefront Correction

The concept of an energy frugal laser weapon uses lowered beam divergence to precisely deliver energy to an optimal spot size on a target resulting in improved efficiency, effectiveness, and magazine depth. A key component in this concept, along with decreased wavelength and increased beam director diameter, is a high average power laser source with very high beam quality, providing near diffraction-limited beam divergence.

A significant characteristic of the operation of solid state lasers is that waste heat which is generated by inefficiencies in the laser pumping process and is deposited in the gain medium must be removed by thermal diffusion to cooled boundary surfaces. Unfortunately, the resulting temperature gradients that drive this diffusion cause index and optical pathlength distortions which pose a serious challenge to high beam quality output. This is in contrast to gas or dye lasers in which the gain medium is swept out of the interaction region by a continuous flow, carrying with it the deposited heat from the laser excitation. Before it is recycled into the laser cavity, the fluid medium can be cooled outside of the optically active region where temperature gradients are of no consequence. Alternatively the heated fluid can be simply expelled from the laser system as is common in gas chemical laser systems. An exception to the case of good optical quality generally achievable with the flowing gas laser medium is that of the nuclear pumped laser where very non-uniform gain excitation results in strong thermal aberrations which are not readily corrected by fast gas flow.

A useful solid state laser amplifier architecture used to reduce the effect of the large optical gradients is the face-pumped, face-cooled amplifier, examples of which are the zig-zag slab and the brewster plate disk. By pumping and cooling through the thin dimension of a high aspect ratio plate, the gain and temperature non-uniformities become approximately one-dimensional. When the extraction beam is then configured to propagate across the resulting index gradients, the optical path length variations are averaged at each point in the beam. Although this arrangement is highly effective, residual distortions caused by, for example, thermal discontinuities at the edges of the apertures and distortions of the optical input and output surfaces still limit the minimum divergence that can be achieved at high average powers.

The successful use of stimulated Brillouin scattering (SBS) phase conjugation for wavefront correction in high average power solid state laser systems has begun to reach a useful maturity and has been effectively demonstrated in the US during the last 5 years. These lasers range in pulse energies between a few hundred millijoules up to 30 J with demonstrated average powers of almost 900 W. These systems, however, have always been based on a master oscillator, power amplifier (MOPA) configuration and have output pulsewidths of <500 ns. For many

applications of high average power lasers, a high peak power is not desirable. In missions such as power beaming to satellites or anti-ballistic missile defense, a continuous wave (CW) or quasi-CW output format optimizes laser energy coupling to the target and maximizes the damage threshold powers of the optical components. However, at the present time, there is not an experimentally demonstrated analog to the SBS MOPA geometry that is adaptable to a CW power oscillator which could yield the near diffraction limited beam quality required for these applications.

The extension of conventional reverse SBS into the long pulse regime is complicated by competition from other nonlinear scattering processes such as stimulated thermal Raleigh scattering (STRS), forward SBS, and stimulated thermal scattering (STS). In the limit of very long pulses or high power CW oscillation, unavoidable small linear absorption in the nonlinear medium generally results in severe competition by STS. However, the strategy of the approach described here is, rather than try to use SBS with extended pulsewidths and try to suppress competition by STS, to design a nonlinear correction scheme based on STS. By using a medium in which the absorption is intentionally set to 5-10% of the incident power, four wave mixing by STS can be used to form an active holographic mirror in the high power oscillator resonator. Since a potentially large amount of power is dissipated in the nonlinear medium, careful attention to thermal management is required. This could be accomplished by configuring the medium in a very thin film over a metallic surface which then serves both as a heat-sink and a reflector to generate the counter-propagating pump wave. The use of the STS holographic mirror as the output coupler in a power oscillator geometry could provide simplified operation and optical configuration over a MOPA geometry.

It is a logical extension to apply STS wavefront correction in high average power lasers to directed energy systems which place the propagation path to a target of interest inside the phase conjugated optical path. Although, this has been successfully demonstrated using SBS, the use of STS in an adaptive pointing and correction scheme could enable the possibility of very long pulse to CW laser operation with near diffraction limited irradiance on target. In high average power CW laser systems that suffer from significant wavefront distortions in the gain medium such as solid state and nuclear pumped lasers, nonlinear active wavefront correction will be absolutely necessary to generate the 1-2 x diffraction limited beam divergence required for proposed missions in directed energy. The use of four wave mixing by STS offers the potential for achieving this in a straightforward power oscillator geometry.

Current or Prior Studies or Analyses

- Phase Conjugation Methods Based on Thermal Nonlinearity in Absorbing Media for High Average Power Solid State Laser Systems, A. Betin, 1993
- Four-Wave Mixing of the Mid-IR Radiation in Media with Thermal Nonlinearity, O.L. Antipov, 1989

3.7 Wavefront Sensors

Critical to advanced optics applications is the ability to measure wavefront phase errors in real time in order to correct distortion and take advantage of the coherence of the light from lasers. The time scales, height of distortion, and transverse resolution of the sensor are all issues

It is important to note that the potential for inexpensive replication of this deformable mirror system is unique. No other adaptive optics or pattern recognition system that has been implemented to date offers reproducibility to this degree and in this manner.

The development of massively parallel, microelectromechanical systems offers a new approach to the production of reliable, high-tolerance mechanical components. Semiconductor fabrication technology has enabled the miniaturization of a variety of sensors and recently, a variety of actuators. Of equal significance is the enabling of large numbers (10^4-10^6) of such micro-sensors and micro-actuators, all fabricated at the same time and on the same substrate. Furthermore, the common fabrication technology enables integration of sensors, actuators, and electronics into monolithic, closed-loop feedback devices with superior performance over open-loop devices. This optics concept will exploit the miniaturization, large numbers and integration techniques for semiconductor fabrication to develop parallel, interconnected micro-actuators coordinated to achieve precision actuation and control at a macroscopic level.

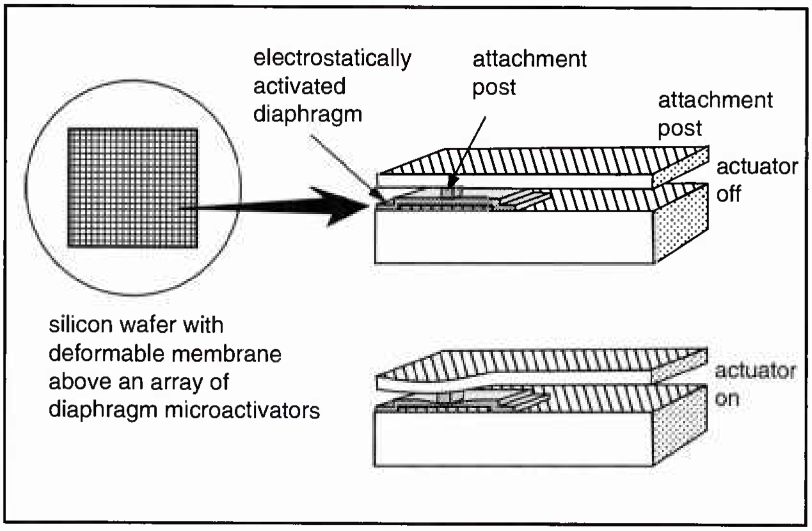

Figure 4. Concept Schematic microelectromechanical deformable mirror device using an array of electrostatically actuated diaphragms.

A continuous mirror membrane spans hundreds of actuators. At right is a schematic of small section of the device. When actuated, an individual actuator locally deflects the membrane mirror by a prescribed amount. Several working actuator arrays have been fabricated and tested in a preliminary research effort.

Adaptive optics systems use a wavefront sensor to measure components of optical phase distortions of imaging systems in real time. These systems have been used to successfully compensate for atmospheric turbulence distortions in astronomical telescopes. However, AO systems using conventional deformable mirror devices have been prohibitively expensive for all but a few applications. By contrast, MEMS mirror arrays are light, inexpensive, low power devices that could enable adaptive optics compensation for a broad new range of applications. Furthermore, MEMS mirror arrays have the potential for faster, more accurate dynamic

response and spatial resolution which will improve the performance of adaptive optics systems. The principal commercial application of optical correlators is pattern recognition, an application of critical importance to the automated manufacturing industry.

3.9 Laser Lethality

Overview and Prognosis

The subject of laser lethality can be considered in three parts:

- Damage - the interaction of the laser beam with the target and the damage it induces
- Susceptibility - the response of the target to the damage
- Responsive threats - the technical and tactical options that may be employed to harden the target against damage, to control the target response to damage, or to reduce the combat effectiveness of laser weapons.

Extensive effort has been invested in understanding each of these areas over the past thirty years, with analyses and experiments ranging from small laboratory scale scientific measurements up to full scale targets attacked by full scale weapons. Much is known and the processes are generally understood, but many critical details are still unresolved. Overall, where a data base exists the performance of specific weapons against specific targets can be predicted to within a factor of two with some confidence. The uncertainties grow larger, of course, as new lasers or poorly described targets are brought under consideration.

The usual lethal mechanism is thermal damage to a susceptible component of the target. Impulse or shock damage have also been considered, but the types of lasers that would inflict those damage modes are no longer being developed. Since lasers deliver energy but not momentum to a target they are normally proposed for employment against thermally soft targets - missiles, satellites, aircraft, people, and sensors. Eyes and imaging sensors are a special class of target. The focusing action of the imaging system makes them uniquely susceptible to damage and they are treated separately.

The mechanisms of beam-target interaction and the damage resulting are fairly predictable, although there are some situations that are difficult to analyze. The largest uncertainties in modeling and in understanding relate to the target response to damage; even here, however, while the details of target response may be difficult to predict, the fact of lethal effect attending a certain damage level is usually confirmed when the process is tested. Techniques for hardening targets against laser damage have been extensively studied and are understood in terms of materials properties and thermal mechanisms. System hardening, design alterations to reduce the response of the target to inflicted damage, has not been thoroughly evaluated. The primary tactical response that has been evaluated is saturation attack, and the impact of that response is predictable. Scenario studies have generally been limited to linear effects - addressing the consequences of the US introducing laser weapons into an otherwise unmodified combat situation. Nonlinear effects, in which the enemy makes major modifications in his tactics and arsenal in response to laser weapons (including the mirror image use of laser weapons, or preferential attack on US laser weapons) have not been well assessed.

When the Soviets were the putative enemy there were extensive efforts to evaluate responsive threat options. The sense of that era was that the Soviets had both the means and the will to respond vigorously to the introduction of a new weapon. In addition to the technical evaluation of potential hardening materials and tests on simple modifications such as polished surfaces, much effort was invested in "what-if" exchanges; red teams proposed speculative threats that called for extreme upgrades in the laser weapon capabilities, and blue teams argued against these super threats on grounds of practicality or cost. With the passing of the Soviet Union the threat model shifted focus to third-world and medium-to-low intensity conflicts, and responsive threats slipped into the background as a factor less likely to materialize in a rapid and sophisticated manner. Present thinking focuses primarily on threats as currently designed or with simple modifications, and threat employment scenarios expand only to include saturation effects. This is a reasonable prioritization in the current reality, but in looking twenty to thirty years into the future it is necessary to open once again the Pandora's box of seriously responsive threats and nonlinear impacts. We know with some confidence that the laser weapons that we can build today will destroy the targets that are out there today. The critical question for the longer term is whether target hardening and other responsive adaptations will effectively defeat laser weapons, or will the performance of laser weapons improve sufficiently to continue their mastery of the targets.

Another dimension of the twenty-to-thirty year threat that needs recognition is the potential reemergence of ICBMs. ICBMs vanished from our threat horizon along with the Soviet Union, and were replaced by the short and intermediate range ballistic missile threats of various second and third world countries. However, the political and military leverage of being able to put the US directly on the firing line is well appreciated, and with or without thermonuclear warheads the option of biological weapon payloads makes ICBMs an effective instrument for political extortion and intimidation.

Over the next two or three decades the major progress that can be expected in understanding laser lethality will occur in the areas of system response to damage and system hardening. These are also the areas most critical to the question of the long term viability of laser weapons.

Damage mechanisms are moderately well understood, but there are still some questions to be addressed. Laser damage studies were aggressively funded between 1970 and 1989, but since then some new laser wavelengths and pulse formats have come onto the scene (diode pumped solid state lasers, with a short wavelength and a repetitive long pulse format, and chemical oxygen-iodine lasers with short wavelengths), and these need to be added to the data base. Presently the Russians have the best capability for studying short wavelength repetitive pulse damage, and have probably gathered an appropriate data base. It remains to be seen whether this resource can be accessed.

Certainly the potential exists for targets to be hardened against laser attack. Factors of several in hardness appear to be available at rational cost, and more can be had if the price is paid. However, the candidate targets for laser attack are thermally soft for a reason - mass is at a premium in aircraft, missiles, and satellites. Adding sufficient mass to achieve truly robust systems works counter to the performance, cost, and mission design criteria. The practical limits on target hardening are not firmly established, and need to be.

Current laser weapon concepts are scoped to achieve lethal effect against unhardened target designs. The logical path for increasing laser weapon capability to stay ahead of target hardening is to attack with smaller spots at higher irradiance, and accomplish a kill with less material damage. This path requires shorter wavelengths, higher beam quality, larger optics, possibly target-in-the-loop phase conjugation, and more precise aimpoint selection and maintenance. More laser power will also be needed, but it appears to be an expensive strategy to attempt to overwhelm hardening with more laser power alone. Technically, we understand how to proceed against the possibility of hardened threats and the prospects for success are reasonable. Additionally, we must better understand the response of the target to damage if we are going to achieve lethal effects with less material attacked.

Ballistic Missiles

The kill mechanism for ballistic missiles is rupturing of a pressure vessel, usually followed by structural collapse of the missile body and further breakup of the structure under aerodynamic and possibly thrust loads. During boost, liquid fuel rockets have fuel and oxidizer tanks under moderate pressure to assist the pumps and prevent cavitation, and solid fuel rockets have the whole motor case under high pressure. Rupturing is accomplished by heating an area of the pressure vessel to a temperature at which it will fail under the pressure load (or under the combined pressure and thrust load). Rupture initiates a propagating crack which spreads the damage over a large fraction of the pressure vessel.

For metal pressure vessels the target material is thin and heat diffuses through it rapidly. It is sufficient simply to heat an adequately large area of the vessel wall until it reaches a temperature, short of melting, where the strength drops off sharply. Energy is not invested in melting or vaporizing and this is an energy frugal process. Composite pressure vessels have thicker walls than metal vessels, and a considerably longer thermal diffusion time, and depending on the time available for an engagement it may be necessary to invest significantly more fluence and penetrate partially by ablation or vaporization of the material in order to reach the failure point.

Damage

Damage is generally understood. A critical factor in the kill mechanism is the development of a propagating crack during the bursting of the pressure vessel. A propagating crack is required in most cases to expand the damage and assure that structural collapse and breakup of the missile will occur. The conditions under which crack propagation will occur for present missile materials and designs have been extensively analyzed and validating experiments have been carried out. To assure crack propagation the blow out area must be greater than some minimum size determined by the material, dimensions, and pressure. The laser must heat that area more or less uniformly, to avoid the development of a local hot spot that would blow out prematurely and vent the pressure without crack formation.

Susceptibility

When pressure vessel failure is attended by a propagating crack the results are dramatic and credibly lethal - the vessel essentially explodes and the missile body folds and probably breaks up.

If a propagating crack fails to develop the pressure vessel will vent and the consequences of that have not been thoroughly evaluated. Pressure loss is certain to have a negative effect on the missile performance, but how much is speculative. At a minimum thrust will be reduced, and probably it will be terminated; in either event it will result in a range short fall of the payload. In solid fuel rockets, if the fuel burn is not extinguished by the venting there will be side thrust developed through the hole, in addition to a reduction of axial thrust. In liquid fuel rockets the tank that has lost pressure, either the fuel or oxidizer tank, will feed the motor less effectively and the burn will at least move off a stoichiometric balance. Additionally, the pump for the affected liquid will probably cavitate and may self-destruct. If the venting hole is beneath the liquid level in the tank the fuel or oxidizer will rapidly drain down to the hole and that will lead to premature engine cut-off. One way or another, there is reason to expect that venting without bursting will be lethal, at least in the sense of a mission kill (range shortfall), but further study of the venting-only situation is warranted.

Responsive Threats

The simplest and most probable response to laser weapons (or any other boost phase defense) is saturation attack, or multiple simultaneous launch. This has been extensively studied, and its impact is understood. Airborne or space based lasers are typically conceptualized to handle some number of simultaneous launches, and barrages in excess of that would require the deployment of proportionally more firepower. However, with time stressed engagements a complication arises. The heat-to-failure kill approach is energy efficient, but it requires an investment of time determined by the diffusion of heat through the wall of the pressure vessel. Metal pressure vessels have short thermal diffusion times and the impact of saturation attack will be simply linear - deliver the lethal fluence in less time. Composite pressure vessels or pressure vessels with composite hardening applied, will have longer diffusion times and this may extract a double price on the laser weapons. If the available single target engagement window is shortened below the diffusion time the laser will be forced to kill via penetration, as contrasted with heating and weakening. This requires melting or vaporizing through a least a portion of the wall at the expense of significantly higher invested fluence. To avoid this penalty it is necessary to invest time in each kill, and under saturation attack conditions this implies that the number of laser weapons in the battle space must be increased to keep pace with the number of launches. It is not sufficient to simply increase the power of a single weapon.

Hardening the pressure vessels by applying a parasitic (non-load bearing) layer of thermally resistant ablative material is an approach that has been much studied. It appears to be feasible, but technically not trivial. Typically, a protective layer over the pressure vessel of about one gram per cm^2 (about 0.5 cm thick) can be invested without impacting the payload or the fuel load (range) too seriously. If this layer must be penetrated by the laser beam before serious damage can begin the fluence penalty can be quite large. The metal in a pressure vessel will typically fail with a fluence investment of about one kilojoule per cm^2; if a one gram per cm^2 layer of ablator must be penetrated first the fluence investment will climb to 10-20 kilojoules per cm^2. Simply heating the ablator and waiting for the heat to diffuse through to the underlying metal wall is a possible tactic. It will require two to three times as much fluence as the metal alone, but that is much less than the penalty of ablating through. In some circumstances patience is not an option. An ablator will have a low diffusion constant (~0.01 cm^2/sec, or less), and the diffusion time through a 0.5 cm layer will be 20 seconds or more. There may or may not be this

much time left during the boost phase of the missile. Additionally, this implies an attack protocol of irradiating the target for a calculated length of time, and then waiting a long period to see if it ruptures - which is not very satisfying.

Nominally, parasitic hardening might increase the target fluence requirements by a factor ranging from two to ten. However, the practicalities of applying parasitic hardening are daunting. The thermally hard materials are brittle and techniques for attaching them to a booster are yet to be engineered. Additionally, many of the attachment devices and configurations that have been proposed introduce thermal short circuits through the ablator to the pressure vessel and would provide little protection against hot spots and pressure vessel venting. Attachment is less of a challenge with the softer, more pliable ablators such as RTV silicone, Teflon, or cork. They can be attached with adhesives, and will expand to accommodate the expansion of the tank under aerodynamic heating. However, these more civilized materials provide only 10-20% as much thermal protection as the brittle materials.

Thermal hardening is not likely to emerge quickly on the ballistic missile scene, and it will probably not be deployed as a retrofit on existing missiles in any event.

Two other proposed approaches to missile hardening are surface reflectivity enhancement and missile rotation. Careful examination of these approaches has shown them to be of limited value for the difficulties they impose on the missile designers and operators. High surface reflectivity is difficult to maintain, and reflective metals become increasingly absorbing as they heat. Depending on the target irradiance this approach could yield a factor of two to three in hardness. Rotation could, in principle, impose a penalty of a factor of three to four, but the missile guidance system must be designed specifically to accommodate rotation.

At the notional level thermal hardening has great appeal, but at the engineering level it is difficult to extract major leverage out of it. These hardening approaches will not save single missiles from destruction; at best they extend the engagement time required of the laser. New ideas could possibly change this picture, particularly in the case of new missiles designed ab initio to resist laser attack. However, even without new ideas or new missiles the combination of modest hardening and saturation attack would require the deployment of greater laser firepower in the battle space.

Even though missile hardening does not appear to be a factor that will excessively stress laser weapons, this is a subject that warrants continued invention, assessment, and intelligence attention as a concomitant to any laser weapon development program. The successful employment of laser weapons will certainly evoke tactical and technical responses of some kind, and prudence requires that those responses be anticipated and accommodated in the weapon design and the deployment concept.

Antiaircraft Missiles - Radar Guided

Antiaircraft missiles (AAMs) have a number of critical subsystems that are susceptible to laser attack: sensors, guidance and control (G&C) electronics, fuses, aerodynamic control surfaces, propulsion, and warheads. Sensors and G&C electronics are generally the easiest to attack, and in the dynamic environment of an air intercept depriving the missile of its sense of direction is likely to induce a miss distance sufficient to protect the aircraft.

Damage

AAMs, unlike ballistic missiles, are not pressurized and do not suffer catastrophic rupture and structural destruction when a spot on the surface is thermally weakened. To achieve a kill the laser beam must penetrate into the missile and thermally damage some critical component.

The missile body is typically constructed of aluminum, and the radome out of a composite or refractory material. The aluminum missile skin is thin, has a high diffusivity, and is more reflective than the steel normally used in ballistic missiles. Penetration will occur at a temperature below the melting point, assisted by aerodynamic forces. The fluence (joules/cm^2) required to penetrate depends on the surface finish and on the wavelength, and is typically in the range of 2-4 kJ/cm^2. Radomes are harder to penetrate, requiring 3-10 kJ/cm^2, depending on the material and the thickness. These penetration fluences are higher than for a pressurized ballistic missile, but the shorter ranges involved in AAM engagements translates into lower required laser weapon power and intensity (watts/steradian). However, the spot sizes are smaller, and the aim point on the target must be more carefully selected in order to damage the selected component.

Clearly an attack through the metal body is preferred, but in the case of self defense engagements the missile presentation is near head-on, which biases toward an attack through the radome.

Once penetration through the skin or the radome has been accomplished the serious work of killing begins. Electronic components are quite soft to thermal attack, and quirky behavior in the missile G&C is usually observed very quickly after the laser beam accesses the electronics. Often the electronics will be packaged in boxes or located behind partitions that must be penetrated before the susceptible components can be attacked.

In a side aspect attack the electronics will be located a short distance behind the penetration point, but in near head-on engagements the susceptible electronics may be spaced a significant distance behind the penetration point on the radome. Smoke and debris generated by the laser beam can accumulate in the radome cavity and provide a measure of shielding. This shielding is a complex process that is not readily analyzed. For large diameter beams (~10 cm) it is not a serious problem; experiments have shown that large holes permit sufficient air recirculation to clear the debris. Small diameter beams (~1-3 cm) , which are essential in energy frugal self defense engagements, have not been studied and it is not known whether debris shielding is an important factor.

In net it requires from three to fifteen kJ/cm^2 to inflict lethal damage on an AAM, depending primarily on the attack aspect angle and the radome material.

Susceptibility

Penetrating the surface of an AAM can, but is not likely to result in lethal effects such as structural failure or excessive unbalanced aerodynamic drag. Damage to the radome will result in a distorted antenna pattern and an angular offset in the sensed target direction. However, the effect of an angular offset becomes less as the range to target decreases and this will not produce a reliably safe miss distance. Damage to the antenna or to the radiating elements behind the radome, similarly, will degrade the guidance capability of the missile, but, unless the damage covers a large area it has uncertain lethality. These degrading types of damage assist in the kill,

but are insufficient by themselves. Damage to the electronics that generate or receive the radar signals, or that process the signals and develop guidance or fusing commands is needed.

The response of an AAM to electronics damage is difficult to predict. Models have been developed that analyze the consequences of specific component failure, but the damage induced by a laser may or may not meet the criteria of the models. The least effect that can be expected is failure to guide. Experiments have shown, however, that wildly erratic guidance commands are more likely, with a radical divert in the missile path.

Responsive Threats

The best investments in thermal hardening are: (1) use thermally hard radome material, and (2) add thermal shielding around the electronics. These steps should be able to increase the lethal fluence to the 20-30 kJ/cm^2 range for an electronics attack. At this level the laser may be forced to employ alternative attack modes, such as a "hot knife" for a structural or aerodynamic kill. ("Hot knife" involves cutting a narrow width swath in the target.)

Antiaircraft Missiles - IR Guided

A laser beam incident upon an imaging sensor, if in the bandpass of the sensor, will pass through a collecting aperture and be focused by lenses or mirrors onto a focal plane where an array of detectors will sense the radiation and pass signals on to a processing system. The focusing results in an irradiance (W/cm^2) or fluence (J/cm^2) at the focal plane that is many orders of magnitude greater than at the collecting aperture, a factor which is called optical gain. Magnifying optics increase the gain by approximately the square of the magnification. Electro-optical imaging sensors have gains ranging from 10^4 to 10^8, depending on their design and function. These sensors operate in various regions of the visible and infrared spectrum, and they must be attacked using lasers operating in the same spectral region. The susceptibility to damage varies greatly with the different types of focal planes. Inflicting damage at the spot where the laser beam hits the focal plane is often not sufficient by itself. That will destroy one to several pixels in an image field that may contain 10^3 to 10^6 pixels. It is often necessary to hit the focal plane hard enough that secondary effects, resulting from plasma formation, cratering debris, or shock generation, destroy all or a large fraction of the focal plane. Disabling a focal plane requires from 10^{-5} to 10 J collected by the aperture, depending on the type of focal plane and the extent of disabling desired.

Countermeasures to laser antisensor weapons emphasize preventing the laser beam from reaching the focal plane. Many approaches have been proposed and extensive development work has been undertaken. There are some protection devices available, but they are far from ideal and much work remains to be done.

Some of the approaches proposed thus far are:

- Narrow band filters, tuned to the laser wavelength
- Neutral density filters to attenuate all laser wavelengths
- Tristimulus filters that transmit only three narrow bands
- Low duty cycle switched filters that transmit only a small fraction of the time at a high prf

- Fast acting electronic switches that respond to laser input
- Nonlinear switches that respond to high irradiance
- Coherence filters that reject coherent radiation

Examples of most of these have been built in the laboratory, and some have been tried in the field. None, thus far, work against the full variety of lasers that might be encountered, but some are effective against lasers that are already deployed.

Some laser antisensor weapons have been deployed on a trial basis (e.g. the British deployment of shipboard argon ion lasers as pilot dazzlers during the Falkland Islands war in 1982; various suspected Soviet deployments in Afghanistan), but it remains to be seen how effective these will be in combat and what form they will take in the future. The contest between antisensor weapons and their countermeasures is still shaping up. It could be an important dimension in future combat.

Other Targets

Satellites

Satellites as currently constructed are particularly susceptible to laser attack. Thermal management is a critical element in satellite design, with solar absorption and reradiation to space balanced by the judicious control of the absorptivity and emissivity of the surface materials. It is necessary to maintain internal temperatures within a narrow range to protect the solid state electronics. Damage to the thermal management surfaces, enough to change the absorptivity and emissivity, will result in destructive temperature excursions and render the satellite nonfunctional. This level of damage requires a fluence of one to several hundred joules/cm^2. More spectacular and prompt destruction sets in at about 1000 joules /cm^2. Pressure vessels (used in some satellites of foreign design) will burst, solar panels will be destroyed, thermal control materials will be completely removed, and antennas will be damaged.

Satellites are not designed to quickly redistribute heat over their whole body, and a laser attack can proceed at a leisurely pace. Typical antisatellite weapons concepts have a 100 second engagement time, which is the exposure time of a low earth orbit satellite to a ground station or an airborne weapon. Target irradiances of several to ten watts/cm^2 are adequately lethal.

Many concepts for hardening satellites have been evaluated. Retrofits on existing designs are difficult to contrive, but new designs can accomplish a reasonable level of hardness. Key elements in hardening are the addition of thermal shields, the use of circulating coolants to make more efficient use of the whole satellite mass as a heat sink for the retained energy, efficient radiators to unload heat, and active control of the temperature of susceptible electronics.

Aircraft

The primary susceptibilities on an aircraft are the pilot and the wing root. The pilot is usually easier to destroy; how easy depends on whether he can be accessed through the windscreen with a laser wavelength short enough to be transmitted by the windscreen. If direct access to the pilot is lacking it is necessary to penetrate into the cockpit. People are very soft to

laser irradiation; several tens of joules/cm^2 on the skin is promptly disabling. However, simply penetrating into the cockpit will likely have a disabling effect because of the hot debris and thermal radiation attending the penetration.

Wing root attack aims at weakening the wing sufficiently to cause it to fold up or to be torn off by aerodynamic forces. For a front aspect attack this requires penetrating the leading edge and heating the main spar; for top aspect attack (as from space, for example) the beam is scanned across the chord (hot knife) to penetrate or to heat and weaken the full width.

Other attack points on an aircraft include the radar and electronic components in the front, and the engine compartment in the rear. The engine itself is thermally hard, but surrounding it are fuel, lubrication, and control feeds that can be damaged.

Hardening aircraft is best accomplished with selective thermal shielding around the areas of greatest susceptibility. Evasive maneuvers can be useful also, particularly to reorient the aircraft such that the airframe shields the pilot from the laser beam.

Surface Targets

Surface targets are not generally the natural prey of laser weapons, but some items are sufficiently soft to thermal damage and valuable enough to warrant laser attack. This circumstance will most likely arise in future space based laser scenarios, where the laser can access targets that are too remote for conventional attack. This requires, of course, that the laser have sufficient magazine depth to be tasked against a spectrum of targets, and that the cost per engagement is much less than envisioned with the current SBL concept.

Ground based radars, command vehicles, communication and power lines, and key individuals are examples of targets that can be attacked. Additionally, aircraft and helicopters on the ground, while less susceptible than when they are in flight, can be damaged sufficiently to keep them grounded for repairs. It is difficult to imagine sinking surface ships, but they have soft topside sensor and communication appendages that are necessary for their combat effectiveness and are susceptible to thermal damage.

In the thirty year time frame a surface target of critical interest to space based lasers may be ground based antisatellite laser weapons (GBL). There are asymmetries in this laser vs laser duel. The GBL has an advantage in being unlimited in weight and prime power, and it can be heavily armored. But the SBL has an advantage in a much superior propagation path. Both lasers must traverse the same atmosphere, but the atmosphere is close to the ground based laser and this impacts the GBL beam propagation severely while it hardly limits the propagation of the SBL at all. To function effectively through the near ground turbulence of the atmosphere the GBL must measure the distortion caused by the turbulence and compensate for it. The sensor required for this compensation is susceptible to dazzling, blinding or destruction. The target tracking sensors are comparably susceptible, and both the GBL and the SBL cannot function without these. The outcome of a GBL-SBL duel will likely hinge on the cleverness of their tracking and turbulence sensor designs. The challenge on both sides is to be able to do high resolution imaging of low radiance objects in the presence of a very intense and rapidly lethal beam. Present sensor designs fail this challenge completely.

of locking on to a target area when mounted on a moving platform (e.g., an aircraft) with no moving parts to the antenna. An additional technology for UWB antennas that will be overcome in the next few years is the need to balance the small size required of the feed section of the antenna with the high voltages that such components must sustain (several MV) for the weapons of the future. In order to improve the voltage hold-off of these components, a better understanding must be developed of the possible theoretical limits of high electric fields per rise time and the ability to approach this limit (10^{16} V/s) using new insulating materials.

Thus, the future HPM UWB antenna will be "dispersionless" over a wide microwave frequency range, it will be steerable, and its shape will be conformal with the carrier platform; i.e., large body sections of wing, fuselage, missile, etc. will be part of the antenna itself.

Hardening

Hardening of systems to HPM effects is technically feasible and often very economical during early development. Retro-hardening of most systems is impractical and would be very costly. Hardening technology has been developed and a few systems are being hardened against most likely threat parameters. The very broad parameter space of potential HPM weapons makes assessment of system susceptibilities and hardening far more difficult than for the nuclear EMP threat. Significant hardening of either US or foreign systems is unlikely until specific deployed threats have been identified or systems are hardened to carry HPM weapons.

Summary

By the year 2015, HPM weapons will be a well established technology with many different configurations possible for the warfighter. The options for deployment will range from missile delivery to aircraft pods and aircraft-mounted systems. Both powerful NB and UWB sources will be available in relatively small package sizes, depending upon the mission. Many sources will be rep-rated to take advantage of target electronic vulnerabilities. Electronically tunable and steerable HPM systems that have their antennas packaged to allow for maximum flexibility in deployment will be possible. Some antenna sections will be part of the weapons delivery package itself fitting smoothly into the airstream. Although it is not expected that these HPM weapons will be as sophisticated as the Buck Rogers phaser guns, we do expect that the technology will support the beginning of a long succession of EM wave, non-lethal devices that will have tremendous value to the future Air Force warfighter.

3.11 Acoustics

The generation of acoustic waves is a subject which has occupied physicists for more than a century. Acoustic energy is not usually considered when one thinks of directed energy devices, possibly because of its venerability, but acoustic waves have properties which make them useful for delay and deny applications. It is also well known that direct conversion from thermal to acoustic power was accomplished by Lord Rayleigh in the last century, and it is believed that conversion efficiencies can be of order of one percent or more. Even a large jet airliner, whose engines have been designed to suppress conversion of thermal energy to acoustic energy, still radiates about 100 kilowatts of acoustic power as the result of burning several kilograms of fuel per second. Further, the wave nature of acoustic phenomena makes it possible to direct and to focus waves. Acoustic waves appear to satisfy, automatically, the requirement of progressive

response, the attenuation of acoustic waves is exponential with distance and is strongly frequency dependent. Thus, sound levels can be made extremely high at one point and yet be tolerable at a distance much less than that determined from inverse square divergence alone. Low frequencies project to larger distances than do high frequencies. Sound systems, therefore, do not suffer as much from the problem of injury to nearby bystanders as do laser systems, for example.

High intensity sound could be used as a warning signal to deter intruders. At higher levels, sound can be used to disrupt audible communications, among intruders. Forcing an intruder group to use radio communications will make monitoring and jamming of communications possible. It has been found, too, that speech intelligibility decreases markedly at high sound levels. Studies[4] done at Wright-Patterson AFB indicated that a human without ear protection experiences pain (at a frequency of 100 Hz) at a sound level of 140 dB, which corresponds to 0.01 w/cm^2. An accidental intruder is unlikely to proceed into areas having higher intensities than 140 dB, and, probably, would be deterred by a sound level 10 times less at 130 dB. At higher levels of sound intensity, nonauditory effects become important, and even ear protection will not prevent severe reactions. Subjects reported that sensations increased very rapidly with sound intensity above 145 dB. At a frequency of 73 Hz the voluntary tolerance of human subjects was reached at 150 dB, or 0.1 w/cm^2. "Alarming" symptoms which were reported at this level included coughing, severe substernal pressure, choking respiration, salivation, pain on swallowing, giddiness, testicular aching, and significant decrement in visual acuity. Subjects complained of marked postexposure fatigue. No long term effects were observed, but one subject continued to cough for 20 minutes, and one subject retained some cutaneous flushing for approximately four hours. Some of these symptoms are likely to be related to an acoustic chest resonance, at approximately 73 Hz. Response to high frequency sound has not been as well investigated, but the data which exist indicate that thresholds for effect are considerably higher than for frequencies in the ~ 100 Hz range.[5] The threshold of pain at 1000 Hz is nearly 10 times higher than at 100 Hz. It is recommended, therefore, that studies of the generation and of the effects of sound waves be conducted at the lower frequencies.

The natural divergence of low frequency sound waves will mandate further large radiating arrays with element spacings of several meters for projection into open areas. Resonant phase-locked analogs of synthetic aperture electromagnetic systems may be useful for such projectors. Experiments indicate that such devices can be fabricated, and that sound intensities as high as 170 dB, 10 w/cm^2, may be possible.

A natural location for effective use of high intensity sound is inside buildings and other enclosed areas, such as weapon carriers or missile silos. Again, frequencies in the 50-100 Hz region should be used. It is possible that damage to structures or devices could occur at the highest sound levels, but damage at levels even as high as 160 dB, which corresponds to a pressure excursion-ion of 0.3 psi, is unlikely unless resonances exist in the structure. Resonances could be found using low intensity test equipment and could be avoided by the selection of an

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4. G.C. Mohr, J.N. Cole, E. Guild, And H.E. von Gierke, "Effects of Low Frequency and Infrasonic Noise on Man." *Aerospace Medicine*, 36, 817(1965).
5. D. Stephens and G. Rood, "The Nonauditory Effects of Noise on Health", in *Handbook of Noise Assessment*, Daryl N. May, Editor, pp285-313, Van Nostrand Reinhold Company, New York, 1978.

appropriate frequency. An intensity of 160 dB exceeds the protected-human intolerance level by a factor of 10.

Methods for the efficient generation, projection, and focusing of high intensity sound should be investigated as a near-term technology which may be useful in delay and denial applications. It is equally important to enlarge the database related to the short- and long-term physiological effects of high intensity sound.

4.0 Conclusions and Recommendations

Conclusions

1. Directed Energy Weapons (DEW), both High Energy Lasers (HEL) and High Power Microwaves (HPM), will have widespread applications in 20-30 years and will be entering the inventory in about 10 years.

Thirty years ago the vision of directed energy weapons, using high energy lasers and high power microwaves, was first seriously engaged by the military. Within a decade the capability of these weapons to destroy or disable targets had been proven, and numerous demonstrations of lethal effect, on increasingly difficult targets, have been carried out since then. The technology needed to implement these weapons in compact packages suitable for integration on combat platforms was lacking in the beginning of this campaign, but is now coming to maturity.

2. HEL and HPM are complementary. Both will be needed and available.

HEL and HPM weapons act through different mechanisms, have distinct advantages and disadvantages, and are largely complementary to each other. HEL weapons generate much narrower beams than HPM weapons. This allows HEL weapons to irradiate selected spots with high precision; conversely, HPM weapons can provide area coverage. HEL weapons must be precisely aimed and pointed; HPM weapons need only be directed generally toward the target. HEL weapons do not operate through clouds while HPM weapons are largely unaffected by clouds. HEL weapons act through a thermal effect to heat, melt, or vaporize selected components, which are generally a small but vital part of the whole target; HPM weapons generate over the whole target high electric fields which couple inside through various openings and disrupt or destroy sensitive electronic components.

3. System improvements will allow DEW to be used on all types and sizes of USAF platforms (A/C, spacecraft, UAV) and will enhance their capabilities in all environments (space and atmosphere).

For the future we see an improved capability to develop optimum laser systems for the mission requirements. This results from improved beam control to achieve higher irradiance on target when propagating the beam through degrading media, giant optics, where advantageous, (e.g. 20 meters diameter) fabricated from thin membranes, diffraction limited beam quality achieved through phase conjugation or electronic adaptive mechanisms, and highly efficient lasers operating at shorter wavelengths moving down to 1μm. Collectively, these advances will give the capability of energy optimized kills. The number of engagements stored in the magazine will expand enormously, or, alternatively, the system can be made more optimal in size and weight for each application.

4. The Airborne Laser (ABL) offers the promise of a practical and effective near term solution to the difficult and crucial TMD/BPI requirement.

The Airborne Laser (ABL) projects laser radiation to tactical ballistic missiles, using thermal energy to produce catastrophic damage to threats within lethal radius. The ABL has the primary mission of Theater Missile Defense using integrated optical technologies to provide speed-of-light capability to destroy theater ballistic missiles during boost phase at long range.

The inherent advantages of this weapon concept are: it destroys the missile during boost phase when it is highly vulnerable and can be easily detected and tracked; it engages the missile prior to any release of submunitions; and debris resulting from missile destruction may fall back on enemy territory.

The ABL program has begun ABL concept designs to be completed in FY 1997. The concept designs being conducted by two competing industry teams address the demonstrator system whch will have traceability and scalability to a system with full operational capability as defined in the technical requirements document (TRD). The demonstrator program will be completed in FY 02. The ABL will probably be the first practical and effective directed energy weapon to be deployed.

5. Global Precision Optical Weapons (GPOWs) have the potential to revolutionize warfare (a paradigm shift) by providing total space dominance over the earth.

Space based (GPOW) or space relayed weapons (Virtual Presence), once the full potential of modern and emerging technology is incorporated, will move beyond their initially motivating role of boost phase defense (as reflected in the current Space-Based Laser (SBL) program) to a multitude of combat activities that have the potential to dramatically change the character of warfare. Global presence with weapons capable of destroying or disabling anything that flies, in the air or in space, or anything on the ground or on the surface of the sea that is unprotected by armor, will drive a new warfare paradigm-one in which the primary imperative of warfare is to control space, and space becomes a major combat arena.

6. DEW can provide increasingly powerful means of defending aircraft against missile attack. These range from infrared countermeasures in the near term, through jammers and antisensor weapons, to weapons capable of physically destroying IR and radar guided missiles in self defense or escort scenarios.

A particularly vital application of HEL and HPM weapons in tactical combat will be the defense of aircraft against missile attack. Aircraft defense can be conducted at relatively short range - a factor conducive to compact directed energy weapon design. HEL weapons will probably evolve through four stages of capability: (1) infrared logic jammers (fractions of a watt); (2) infrared antisensor weapons capable of destroying IR sensors (tens of watts); (3) short range heavy duty weapons capable of destroying IR or radar guided missiles in self defense scenarios (tens of kilowatts); (4) medium range heavy duty weapons capable of destroying IR or radar guided missiles in escort defense scenarios (megawatt class).

Recommendations

1. Promising approaches have been identified for aircraft defense, theatre missile defense, and global force projection. These concepts should be developed through detailed concept studies.

a. Aircraft Defense. Directed energy technology currently exists capable of defeating IR-seeking missiles through jamming or sensor kill. HPM transmitters for jamming or disabling electronic systems at moderate ranges are under development. Concepts have been defined showing a development path from present technology through systems capable of disabling or destroying vital missile components, ultimately to conformal phased arrays of high power diodes

integrated into the structure of the aircraft (FotoFighter), providing capabilities ranging from surveillance and tracking to thermal kill of attacking missiles. In addition to detailed analysis of these concepts, specific studies are required to define the most promising path toward cost reduction of diode arrays and development of high precision threat detection and tracking systems.

b. GPOW/ Virtual Presence. The Airborne Laser (ABL), developed as a boost-phase, theater missile defense weapon, will probably be the first practical DE weapon to be deployed. Once the full potential of current and emerging technology is realized, space-based (GPOW) or space-relayed (Virtual Presence) DE weapons will move beyond their initial role in boost-phase defense to a multitude of combat missions. With the potential to destroy or disable anything that flies in space or in the air, or striking any target on the surface of the land or sea, these weapons will revolutionize the character of warfare.

Conceptual studies are required to define development plans for the technologies needed to realize this vision in greater detail. In particular, significant advances are needed in reducing the costs of launching payloads to orbit, and in developing lighter-weight, "energy-frugal" laser systems. Two of the technologies needed for these systems require radical innovation: multi-meter sized optics with diffraction limited performance, and techniques for pointing and tracking to 50 nanoradian accuracy. Concepts for achieving the required technical performance should be developed and evaluated.

c. UAV-TMD. If compact, energy frugal DEWs can be developed, a UAV-based weapon for theatre missile defense becomes an attractive option. The weapon will need to be much more compact and less expensive than the ABL, and it will have a shorter lethal range and a smaller magazine. It is attractive because it has a long on-station loiter time, and, since the UAV flies at high altitude and engages at shorter range, atmospheric distortion is much less of a problem, and it will not require the sophisticated atmospheric compensation needed for the ABL. Being unmanned and relatively inexpensive, it will be attritable, and can be forward based over hostile territory, where its reduced engagement range will be less limiting. Concept studies are required to refine designs for this approach, and to identify a program for the required technology development.

2. Develop and demonstrate compact, high power diode pumped solid state lasers. Such lasers, in several different versions are attractive for many of the laser weapon applications envisioned for the future.

Diode pumped solid state lasers have been developed at the several kilowatt power level. Weapon applications call for lasers ten to one thousand times higher in power. The primary inhibiting factor in achieving those high powers is the cost of diode pump arrays, a problem which is addressed in another recommendation. However, there are a number of engineering issues and design requirements that attend a major power extrapolation, particularly given the size and weight restrictions imposed by the platforms, and these need to be addressed in detail, solved, and demonstrated. Design constraints and performance requirements increase in difficulty as we progress from Aircraft Defense Against Missiles (ADAM) through the UAV based TMD weapon, to the global projection space weapon (GPOW). Conceptual designs on all of these weapons should begin in parallel, but the engineering developments of critical components should be staggered sufficiently that the more challenging problems can benefit from

the solutions to easier ones. For each of the platforms a sequence should be followed that progresses through (1) design studies, (2) innovation and laboratory scale demonstrations of solutions to critical problems, (3) revisit the design studies in light of data and experience acquired during the innovation/demonstration phase, and (4) undertake system development. Some key components requiring innovation and demonstration can be identified ab initio: (a) laser heads and optical configurations, (b) beam quality control, (c) ultra-lightweight beam directors, (d) power supplies, and (e) very importantly, thermal management. This process will go to completion first on the ADAM weapons, and this thrust should address two levels of compact DPSSL weapon design suitable for integration into aircraft: a 40 kW version, with a goal of 200 kg mass and less than 0.4 m^3 volume, and a 1 MW version with a goal of 2000 kg mass and less than 4 m^3 volume. The 40 kW version should be implemented in hardware as soon as a suitable design is available. Implementing a 1 MW version, and also the UAV weapon, must await progress in the diode cost reduction effort. Implementation of the GPOW weapon requires both progress in diode cost reduction and development of membrane optics technology, although laboratory demonstration of the laser itself can proceed without the membrane optics.

3. The Air Force, in collaboration with the other Services and ARPA, should support a program with the goals of reducing the acquisition costs of laser diode pump arrays to:

- Less than $2/ peak watt and $25/ average watt by 2000; and
- Less than $0.2/peak watt and $2/average watt by 2005.

Laser diodes offer a path to greatly enhanced solid state laser performance, but are not affordable for these missions, unless the cost of the diode pumps can be radically decreased. This is not a new or unique observation. In 1985 when laser diode costs were on the order of $300/peak watt and $2000/average watt, the Service laboratories recommended to OSD a diode array producibility program. The recommendation was partly implemented by the Balanced Technology Initiative (BTI) in 1988-1992 as a task under the IRCM program. Three contractors were chosen to develop production programs to a common Service specification and activity through an initial pilot run was executed with two of these (Applied Solar and SDL Inc.). All of these efforts were aimed at so-called rack and stack arrays in which linear arrays are literally piled up to form a two dimensional array. This activity resulted in diode arrays at costs which were for 1 - 10 J prototype lasers; ~ $10 - 15/peak watt and $75/average watt. These costs are, however, prohibitive for production lasers, either for military or civilian usage.

Needed in the immediate future (1995-2000) to promote wide commercial and DoD usage is an activity to reduce the cost to ~ $2/peak watt and $25/average watt. This would also make diode pumped lasers at the joule/pulse or 10's of watt levels cost competitive in acquisition cost with older technology lamp pumped lasers and promote; commercial markets for diode laser pump arrays at the $100 million/yr level which would heighten interest in the commercial markets in even more improved diode pumped lasers, and provide commercial incentives for the diode producers to reduce costs even further by their own efforts.

While a great improvement over early costs, rack and stack arrays intrinsically involve mechanical assembly as well as semiconductor fabrication; there is a limit on how far costs can be reduced for this approach; while opinions vary on asymptotic cost for rack and stack, it is in a range of $0.80 - $1.0/peak watt and ~ $10/average watt. This is still a very high cost for lasers in the 100-10,000 J/pulse range.

An intrinsicly different approach to diode arrays architecture is to make the array as an intrinsically two-dimensional device of wafer size. This approach has potential to reach costs below $0.10/peak watt, but needs considerable development. Two sequential activities should be planned, one for 1995 - 2000, with a follow-on for 2000 - 2005 in order for an affordable diode pump laser technology to be in place by the start of the second ten year period when work on more robust aircraft self defense systems is needed. The first phase would concentrate on defining the most promising two-dimensional array architectures in terms of performance and producibility . The second phase would concentrate on a producibility program.

4. Development of phased arrays of laser diodes must be emphasized.

A solid state laser in which the laser is an array of laser diodes directly radiating in phase has the potential for higher efficiency by a factor of two than diode pumped lasers. This has been evident for some years; what has been difficult to implement is achieving robust phase locked operation. The Phillips Laboratory and Wright Laboratory have both had ongoing activities in this area. In addition, the explosion of interest commercially in fiber optical communications has led to the rapid reduction to practice of modulators, phase shifters and other components which did not exist a few years ago. Some of the lower power non-linear optical phase conjugation approaches which are only now emerging from basic research also offer potential for controlling the phase of an array of emitters.

The long term potential of this area is so great that continued development is merited. It is very important that the DoD activities remain cognizant of the ongoing developments in other areas which can dramatically improve the ability to meet the longer term goals and not be focused exclusively on more engineering-oriented short term approaches with limited potential.

5. Adaptive optics and phase conjugation should be developed and exploited for weapon beam delivery to target.

Adaptive optics and phase conjugation are two technologies that figure centrally in some of the present and most of the future applications of directed energy for the correction of path turbulence or figure imperfections in optical elements. In particular, these techniques permit the use of lightweight, cheap, imperfectly figured optical elements such as very large inflatable membrane optics. Major advances are required in both of these demonstrated technologies. Phase conjugation must be extended to operation at high average power, near CW laser systems by substituting nonlinear interactions such as stimulated thermal scattering (STS) for stimulated Brillouin scattering (SBS), the latter of which is more optimally suited for high peak power, short pulse operation. Work in this area should begin with the demonstration of medium average power (~1kW) solid state laser systems using STS wavefront correction and having near diffraction limited output. Present lasers in this power range have beam qualities which are at least 10X poorer than diffraction-limited. Continued development should then proceed to demonstrate scaling to the higher average powers required by DEW's as well as incorporating STS based adaptive pointing and correction to target techniques. Alternative implementations of conventional adaptive optics should pursue advanced technologies which could inexpensively yield thousands or even hundreds of thousands of adaptive elements with improved temporal bandwidth, using either "light valve" devices or microelectromechanical (MEM) fabrication techniques.

6. Joint efforts should be initiated between the USAF and NASA directed toward the development of large, lightweight, space-deployable optics.

The concept of the energy frugal directed energy weapon from space (GPOW and Global Presence) is based on the ability to deliver energy to high irradiance, small spots on target. A key component to enable this type of system is a large, lightweight beam director such as a 20 m mirror for high energy lasers (HEL) or a 1-10km antenna for high power microwave generators (HPM). Membrane optics which could be directly inflated or which incorporate inflatable support structures offer the potential meet the proposed DEW requirements. Development in the area of large membrane optics should initially involve tests on the ground within a program which progressively demonstrates scaling toward the mission size requirements. Survivability is an important consideration in the choice of materials and construction and should take into account long term exposure to the anticipated barrage of fine scale solid debris and solar radiation loads. Material surface quality and the ability to provide a high reflectivity surface at the laser wavelength will also guide this choice. Significant innovation will be required in the area of mirror deployment, addressing the challenges of folding and unfolding the structure for transport and deployment. For example, advanced schemes have been proposed in which the very large membrane mirrors might actually be manufactured in space where electrostatic fields could accurately guide the polymerization of liquid precursor materials. Continued activity should consist of prototypical development in which methods of surface figure control such as that achieved by electrostatic fields need to be explored. Advanced precision station keeping techniques should be developed for the stabilization of extremely large HPM antennae. Optical diagnosis such as high resolution range finding could be considered to provide feedback for shape control. Finally, all of the described activity should be closely accompanied by development and testing of adaptive optical correction systems using, for example, nonlinear phase conjugation, which will be required to provide diffraction-limited optical beam delivery, compensating for figure errors in the large, lightweight optics.

7. An experimental evaluation should be undertaken of the lethality of small diameter, high irradiance, short wavelength radiation against antiaircraft missiles.

Energy frugal kill is a vital enabler of compact aircraft defense weapons. This requires a small spot size on target and implies a short wavelength laser with high irradiance. Many experimental and theoretical evaluations of laser lethality have been carried out over the past thirty years, but the accumulated data base is inadequate on small spots and short wavelengths. This deficiency needs to be rectified. Experiments should be conducted with short wavelength lasers, using the expected irradiances and spot sizes, against real targets. Wind over the target will be an important aspect of these experiments, since debris shielding of the laser beam and debris clearing by wind are competing factors during deep penetration.

8. HPM weapons have potential application to all mission areas that depend on advanced electronics. Development of a variety of HPM sources is required to provide the parameters required for use on delivery platforms ranging from aircraft, UAVs, and missiles to people. The performance, efficiency, size, and reliability of sources must be improved. Pulsed power and antenna size are presently the limiting components and need strong emphasis in the near term. Basic research is required to support HPM source technology advances that will increase power and flexibility while decreasing size and weight. HPM weapon potential needs to be demonstrated in realistic scenarios and fratricide issues addressed.

The threat of RF to electronics in military and commercial systems is real and needs to be considered in system development and operational concepts. Susceptibilities need to be identified, modeling and simulation tools developed, and hardening technology provided to SPOs. The impact of HPM on unhardened commercial systems important to military operations needs to be assessed and mitigation strategies developed. The HPM threat will probably grow in a stepwise fashion taking advantage of the weakest links at any given time. This will require astute planning to allow affordable upgrades in system hardening as required.

Appendix A

Panel Charter

The Directed Energy Panel will develop a vision of future Air Force applications for directed energy, targeting applications for the 10-, 20-, and 30-year time frames. The panel will identify fields of rapidly changing directed energy technology and assess their impact on the Air Force, with a goal of identifying those areas which will most likely revolutionize the 21st century Air Force. The panel will recommend specific actions that will begin or redirect the process of developing the required enabling technologies where the commercial world is unlikely to invest.

Appendix B

Panel Members and Affiliations

SAB Members

Dr. Gene McCall
Los Alamos National Laboratory

Dr. Alexander Glass
Lawrence Livermore National Laboratory

Senior Civilian Participant

Mr. Darrell Spreen, USAF
Phillips Laboratory

Ad Hoc Advisors

Maj Gen Donald Lamberson (Ret)
Chairman

Mr. John McMahon
Navy Research Laboratory

Dr. Walt Sooy (Ret)
Lawrence Livermore National Laboratory

Dr. Clifford (Brent) Dane
Lawrence Livermore National Laboratory

Executive Officers

Lt Col Mike Crawford, USAF
Phillips Laboratory

Lt Col Dave Hincy
USAF Scientific Advisory Board

Technical Editor

2Lt Dennis Rand

Appendix C

Panel Meeting Locations and Topics[6]

01 March Kirtland AFB, NM

- Prior Studies - Power Beaming - Semiconductor Laser Technology - Non-Linear Optics - Stand-off Detection and Imaging - Guidestar - Acquisition, Pointing, and Tracking

24 March Kirtland AFB, NM

- US & Russian Reactor Pumped Lasers - FotoFighter - Power Beaming - Virtual Presence

20-21 April Kirtland AFB, NM

- Infrared Countermeasures - Power Beaming - Laser Communications - Space Debris - Acoustics - Starfire Optical Range - Airborne Laser & Boost Phase Intercept

3-5 May Maxwell AFB, AL

- Space-Based Lasers - Interactions with Other Panels & Working Groups

9 June Kirtland AFB, NM

- Joint Meeting with Sensors Panel - Lasers Deployed with Marine Expeditionary Unit in Somalia - Electric Chemical Oxygen Iodine Laser - Joint Meeting with Munitions Panel Chair

6. Does not include Panel Chair Meetings or the Summer Study Session.

Appendix D

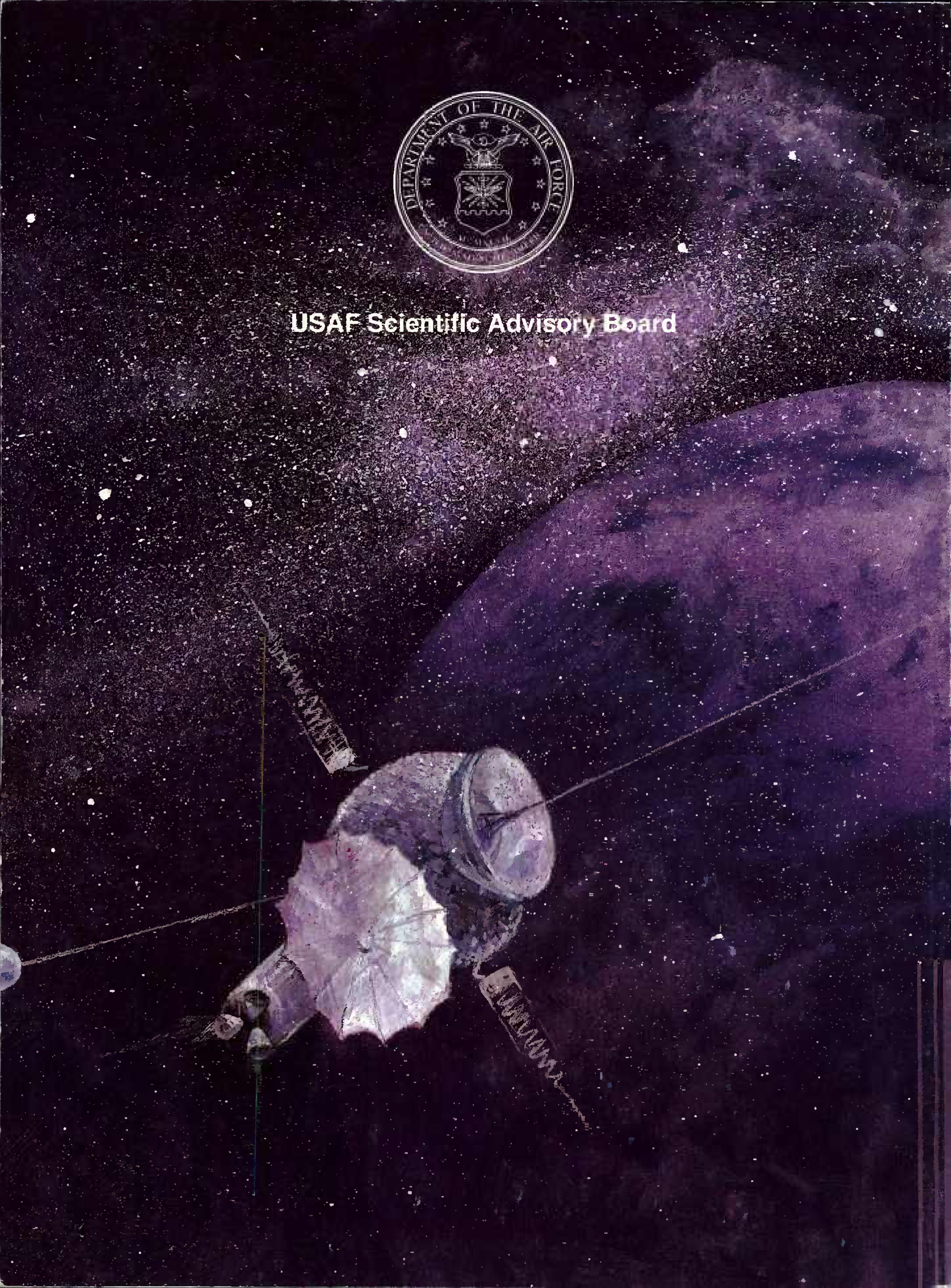
List of Acronyms

Acronym	Definition
AAM	AntiAircraft Missile
ABL	AirBorne Laser
ABLE ACE	AirBorne Laser Extended Atmospheric Characterization Experiments
ABLEX	AirBorne Laser Experiment
ADAM	Aircraft Defense Against Missiles
AFB	Air Force Base
AO	Adaptive Optics
ARPA	Advanced Research Projects Agency
ASMD	Anti-Ship Missile Defense
ATBM	Anti-Tactical Ballistic Missile
ATIRCM	Advanced Technology InfraRed CounterMeasures
ATLAS	Advanced Tracking LASer
BASS	Bulk Avalanche Semiconductor Switches
BHP	mixture of Hydrogen Peroxide and Potassium Hydroxide
BMDO	Ballistic Missile Defense Organization
BPI	Boost Phase Intercept
BTI	Balanced Technology Initiative
BU	Boston University
C^3	Command, Control, and Communications
C^4I	Command, Control, Communications, Computers, and Integration
COIL	Chemical Oxygen-Iodine Laser
CONOP	CONcept of OPeration
CONUS	Continental United States
CPU	Central Processing Unit
CSAF	Chief of Staff, Air Force
CW	Continuous Wave

CW	Continuous Wave
D&D	Decontamination and Decommissioning
D^4	Deny, Disrupt, Delay, and Destroy
DAPKL	Diode Array Pumped Kilowatt Laser
DEW	Directed Energy Weapon
DoD	Department of Defense
DoE	Department of Energy
DPSSL	Diode Pumped Solid State Laser
EM	ElectroMagnetic
FLIR	Forward Looking InfraRed
FOC	Fully Operational Capability
FOV	Field Of View
FY	Fiscal Year
G&C	Guidance and Control
GBL	Ground Based Laser
GEO	Geosynchronous Earth Orbit
GPOW	Global Precision Optical Weapon
HDTV	High-Definition TeleVision
HEL	High Energy Laser
HPM	High Power Microwave
HPSLT	High Power Semicondutor Laser Technology
ICBM	InterContential Ballistic Missile
ICF	Inertial Confinement Fusion
IFF	Identify Friend or Foe
IOC	Initial Operation Capability
IR	InfraRed
IRST	InfraRed Search and Track
JMNS	Joint Mission Needs Statement
JROC	Joint Required Operational Capability
JSTARS	Joint Surveillance, Tracking, And Reconnaissance System
LEO	Low Earth Orbit

LIDAR	LIght Detection And Ranging
LLNL	Lawrence Livermore National Laboratory
LOS	Line Of Sight
LPI	Low Probability of Intercept
MCG	Magneto-Cumulative Generator
MEMS	Micro-ElectroMechanical Systems
MHD	Magneto-HydroDynamic
MILO	Magnetically Insulated Line Oscillator
MIR	Micropower Impulse Radar
MIRV	Multiple Independently-targetable Re-entry Vehicle
MNS	Mission Needs Statement
MOB	Main Operating Base
MOPA	Master Oscillator Power Amplifier
mph	Miles Per Hour
NB	Narrow Band
Nd	Neodymium
OPO	Optical Parametric Oscillator
ORD	Operational Requirement Document
OSAR	Off-Axis Scattering and Reflection
P/T	Pointing and Tracking
PCM	Phase Conjugate Mirror
PDR	Preliminary Design Review
PGM	Precision Guided Munitions
POM	Project Objective Memorandum
R&D	Research and Development
RCS	Radar Cross Section
RF	Radio Frequency
RTV	Remotely Targeted Vehicle
S&T	Science and Technology
SAB	Scientific Advisory Board
SAM	Surface-to-Air Missile

SBL	Space Based Laser
SBS	Stimulated Brillouin Scattering
SOR	Starfire Optical Range
STRS	Stimulated Thermal Raleigh Scattering
STS	Stimulated Thermal Scattering
TBM	Tactical Ballistic Missile
TI	Texas Instruments
TIP	Technology Insertion Program
TMD	Theatre Missile Defense
TOA	Total Obligation Authority
TRD	Technical Requirements Document
UWB	UltraWide Band
VCSAF	Vice Chief of Staff, Air Force
Yb	ytterbium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